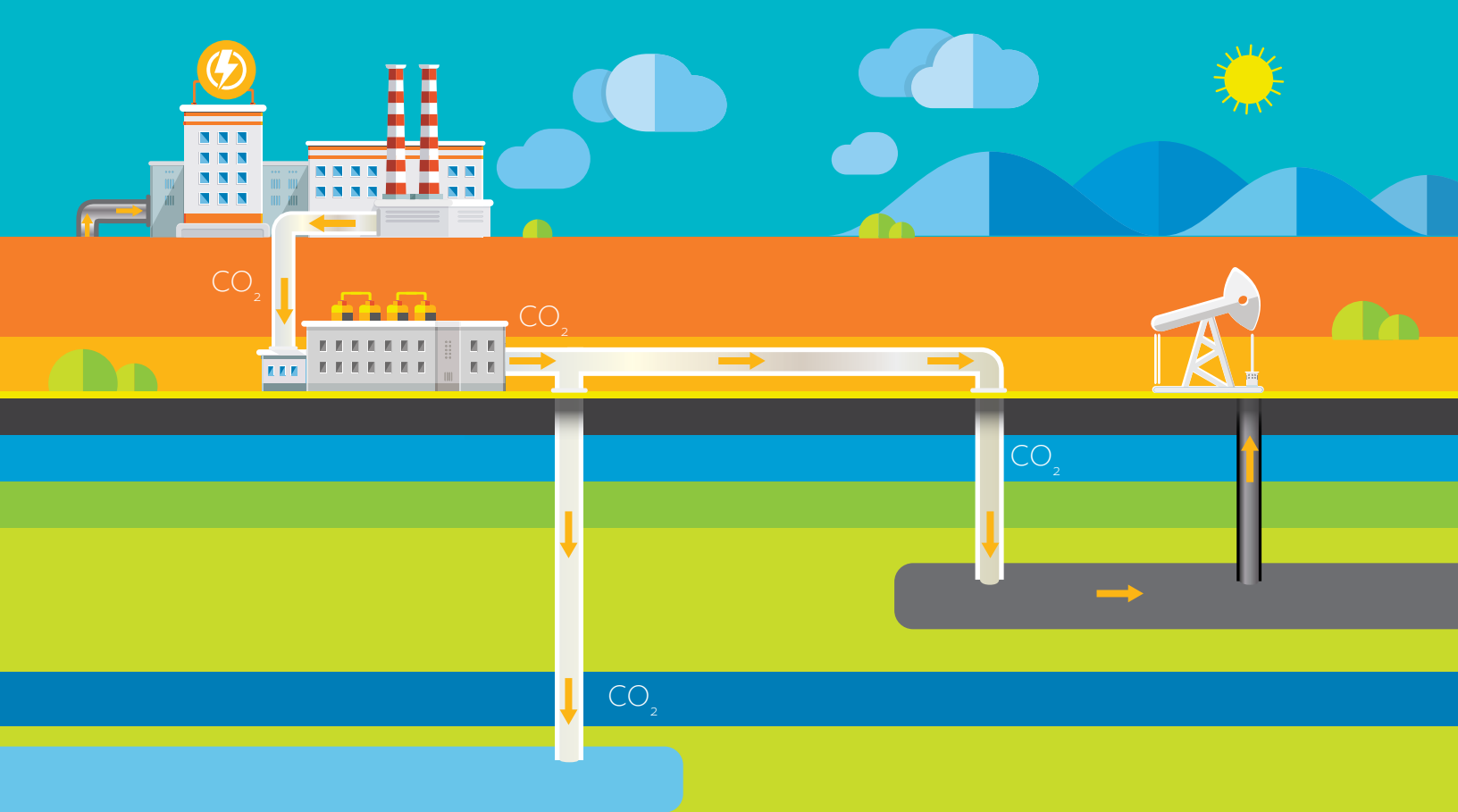




CARBON DIOXIDE-ENHANCED OIL RECOVERY IN INDONESIA

AN ASSESSMENT OF ITS ROLE
IN A CARBON CAPTURE AND STORAGE PATHWAY

DECEMBER 2019

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ABBREVIATIONS

ADB	Asian Development Bank
BECCS	Bioenergy with CCS
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CO ₂	carbon dioxide
CoE	Center of Excellence for carbon capture and storage and/or carbon capture, utilization, and storage, within the Ministry of Energy and Mineral Resources of Indonesia
PRC	People's Republic of China
EOR	enhanced oil recovery
GHG	greenhouse gas
IEA	International Energy Agency
ITB	Institut Teknologi Bandung (Bandung Institute of Technology)
LEMIGAS	Lembaga Minyak dan Gas Bumi (Indonesian Research and Development Centre for Oil and Gas Technology)
MEMRI	Ministry of Energy and Mineral Resources of the Republic of Indonesia
MMP	minimum miscibility pressure
MRV	measurement, reporting, and verification
NDC	nationally determined contribution

WEIGHTS AND MEASURES

b/d	barrel per day
Gt	gigaton
km	kilometer
Mb/d	million barrels of oil per day
Mboe/d	million barrels of oil equivalent per day
mmscf/d	million standard cubic feet per day
Mt	metric ton
MMT	million metric ton
TWh	terawatt hour

EXECUTIVE SUMMARY

Enhanced oil recovery through the injection of carbon dioxide (CO₂-EOR) is a proven technology for rejuvenating the production of oil at mature oilfields but can also provide a means of permanently storing carbon dioxide (CO₂) as much of the gas injected remains incidentally trapped in the field. The use of the technology to mitigate climate change—referred to here as CO₂-EOR+—is attracting interest around the world. As a type of carbon capture, utilization, and storage (CCUS) technology, it could make an important contribution to efforts in Indonesia and elsewhere to curb emissions of CO₂—the leading greenhouse gas (GHG)—over the long term and to mitigate climate change. It is widely seen as a stepping stone to other types of carbon capture and storage (CCS) that do not necessarily involve any use of CO₂.

At a minimum, CO₂-EOR+ requires the CO₂ to come from an anthropogenic source, such as a power station or a natural gas processing plant (since gas extracted from a reservoir often contains significant amounts of CO₂). CO₂-EOR always results in some CO₂ being stored permanently in the field, even if operated in such a way as to maximize oil production without regard to how much CO₂ is stored. But for use of the technology to qualify as a genuine climate mitigation measure, several additional activities need to be undertaken before, during, and following CO₂ injection, including additional measurement, reporting, and verification activities. For oilfield operators to opt for anthropogenic sources of CO₂ and to choose to maximize storage of that gas at all stages of the project cycle, they either need to be given a financial incentive, such as a carbon tax or price, or to be required to do so through regulation.

The use of CO₂-EOR remains relatively limited for now, but is growing rapidly, both in the United States (US), where it was first developed, and in some other countries. And CO₂-EOR+ is starting to take off as new projects are designed with the dual goal of boosting oil production and storing the CO₂, usually in response to financial incentives. There are currently 14 large-scale CO₂-EOR+ projects in operation around the world with a total injection capacity of around 35 million metric tons (MMT) per year. Ten of them are located in North America, of which eight are in the US; the largest in the world is at the Lula and/or Sapinhoa offshore oilfield in Brazil.

CO₂-EOR+ is a potentially attractive win-win solution for Indonesia, by slowing or halting the decline in oil production while addressing the urgent need to curb the country's rapidly rising CO₂ emissions. Indonesia is a long-standing producer of crude oil, though production has fallen steadily for more than 20 years. There may be extensive opportunities for enhanced oil recovery (EOR), including using CO₂, given the maturity

of many of the country's oilfields. The only type of EOR that has been deployed so far in the country on a commercial scale is steam flooding. At the same time, energy use and GHG emissions in Indonesia are expected to continue to grow briskly in response to economic and population growth and continuing heavy reliance on coal and other fossil fuels. Under its nationally determined contribution to the United Nations Framework Convention on Climate Change, the Government of Indonesia is committed to reducing national emissions of CO₂ and other GHGs by 29% below a baseline trend by 2030 unconditionally and by up to 41% on the condition that international support for finance, technology transfer, and capacity building is made available.

The main potential sources of anthropogenic CO₂ in Indonesia are natural gas and associated oil and gas processing plants, and industrial processes that involve the conversion of hydrocarbons. Power stations and petrochemical plants, including fertilizer factories, could also capture and supply CO₂ for CO₂-EOR+. The processing of natural gas is likely to be the cheapest source of high-purity CO₂ now and in the future. The CO₂ has to be removed (along with other impurities) before the natural gas can be distributed and consumed, so that the only additional cost is transporting it to the oilfield for injection. The availability of CO₂ from gas processing is likely to grow as several of the gas fields that are expected to come on stream in the coming years have particularly high CO₂ content.

A number of studies have already been carried out to assess the potential for CO₂-EOR+ in Indonesia and to match sources of CO₂ with oilfields. The large amount of oil remaining in most of Indonesia's mature oilfields suggests that there is significant technical potential, though the economic potential is likely to be far smaller, especially at low oil prices. The cost of procuring the CO₂ is particularly important to the economic viability of deploying the technology. The most promising candidates for CO₂-EOR+ projects are mature fields with declining production that are located in close vicinity to low-cost sources of CO₂, such as natural gas processing plants.

The critical first step in the process of developing CO₂-EOR+ in Indonesia is to launch an initial pilot project. Commercial projects will only follow if at least one pilot and demonstration project has been operating successfully for several years. The learning and experiences from pilot and demonstration projects will be of enormous value in helping operators design commercial projects and helping policy makers draw up an effective legal and regulatory framework.

A pilot project at the Sukowati oilfield located in East Java has been proposed. The project consists of four production wells and a CO₂ injection well. If the pilot proves to be successful, a commercial-scale project using a miscible process is envisaged, involving the use of all 35 existing production wells and drilling new CO₂ and water injection wells. The CO₂ needed for the pilot project would be sourced from the Sukowati field itself. (The gas currently produced from the field contains about 40% CO₂).

Since CO₂-EOR+ is a new activity in Indonesia, it requires the development of a comprehensive legal and regulatory framework. A draft presidential decree setting out a general framework for CCS was completed in March 2019—the first of its kind in a developing country—building on existing regulations governing the upstream sector and industrial activities. The primary objective of the decree is to establish a performance-based system of permitting for the storage of CO₂. It sets out the standards by which CCS projects shall be permitted with the objective of mitigating associated risks, covering both pilot and full commercial CCS projects. The decree exempts pilot projects involving the injection of less than 150,000 tons of CO₂ from certain requirements and allows the regulator to waive other requirements on a case-by-case basis. The development of a more comprehensive framework at a later stage is expected to benefit from the lessons learned from the pilot projects.

There is also a need to review and recommend specific policies and tax incentives for CO₂-EOR+ in Indonesia. For large-scale commercial projects to take off, a significant financial incentive in the form of a carbon price or tax credit will probably be necessary, especially if oil prices fall. The development of human capital will also be an important element in achieving the successful demonstration and subsequent large-scale deployment of CO₂-EOR+ technology in Indonesia.

I. INTRODUCTION

The Asian Development Bank (ADB) provided technical assistance to the Republic of Indonesia under the program entitled *Pilot Carbon Capture and Storage Activity in the Natural Gas Processing Sector*.¹ Carbon capture and storage (CCS) is a suite of emerging technologies that involves sequestering carbon dioxide (CO₂)—the leading greenhouse gas (GHG)—from fossil-fuel combustion or industrial processes and storing it permanently underground. It is widely regarded as a potentially important means of reducing anthropogenic emissions of CO₂, alongside a shift in energy use to less carbon-intensive sources, improvements in CO₂ efficiency, and energy conservation. A large reduction in worldwide emissions is urgently required to meet the internationally agreed goal of limiting the rise in global temperatures to below 2°C under the Paris Agreement on climate change. ADB seeks to facilitate the inclusion of CCS in national low-carbon growth strategies and policies, and its eventual deployment in its member countries.

The purpose of this report is to provide a broad initial assessment of the potential for CO₂-enhanced oil recovery (EOR) to be deployed in Indonesia as a form of CCS, thereby contributing to the country's climate policy objectives. CO₂-EOR is an established technology for boosting the recovery of oil at mature oilfields through the injection of CO₂, but it also provides a means of storing CO₂ since much of the gas injected remains permanently trapped in the field. CO₂-EOR used with the aim of storing CO₂ from anthropogenic sources (referred to in this report as CO₂-EOR+) is a type of carbon capture, utilization, and storage (CCUS) technology, itself a variant of CCS (pure CCS does not involve any use of the CO₂). It is expected that CO₂-EOR+ will continue to play a major role in supporting the initial deployment of CCUS in the United States (US), where it is already well established, and elsewhere.² CO₂-EOR+ is widely seen as a stepping stone to other types of CCS.

This assessment evaluates the relevance of CO₂-EOR+ as a climate mitigation strategy in Indonesia, which would most likely be based initially on CO₂ captured during the processing of natural gas produced from onshore oil and gas fields. A successful pilot project will be critical to providing the data and experience needed to deploy CO₂-EOR+ and other types of CCS projects on a large scale in the country. The report is also intended to inform all potential stakeholders in CCS and climate policymaking generally in Indonesia and further afield of the opportunities and challenges that lie ahead.

¹ ADB. Indonesia: Pilot Carbon Capture and Storage Activity in the Natural Gas Processing Sector (TA 9189-INO). <https://www.adb.org/projects/49204-002/main>.

² International Energy Agency. Carbon Capture, Utilisation and Storage. <https://www.iea.org/topics/carbon-capture-and-storage/>.

II. THE TECHNOLOGY

A. Carbon Capture, Utilization, and Storage to Mitigate Climate Change

CCUS involves the capture of CO₂ from fuel combustion or industrial processes, its transportation by ship or pipeline, its use as a resource to create valuable products or services, and its permanent storage deep underground in geological formations. CCUS is generally categorized as a type of CCS—a suite of technologies that prevent CO₂ emissions from entering the atmosphere, while pure CCS does not involve any utilization of the CO₂. The overall cost of CCS can be substantially reduced when the CO₂ is used for an industrial purpose, such as EOR, before being permanently stored.

CCUS technologies can also provide a means of removing CO₂ from the atmosphere, i.e., “negative emissions,” to offset emissions from sectors where direct abatement is not economically or technically feasible, such as in aviation transport or agriculture (International Energy Agency, 2017). Limiting the increase in global temperature to 1.5°C—the ambition set out in the Paris Agreement—would probably require the eventual deployment of technologies to actually remove carbon from the atmosphere in addition to nearer term actions to completely phase out emissions of GHGs. Bioenergy with CCS, also known as BECCS, is the most promising negative emissions technology. BECCS involves the conversion of biomass, which extracts CO₂ from the atmosphere as it grows, to chemical products or other forms of energy with the resulting CO₂ captured and geologically stored. Possible applications of BECCS include power generation, combined heat and power, pulp and paper mills, lime kilns, ethanol plants, biogas refineries, and biomass gasification plants (footnote 2).

Although it is not yet widely deployed, CCUS is expected to play an important role in meeting energy and climate goals worldwide in the coming decades. It is seen as the only option to reduce CO₂ emissions to a near-zero level from fossil power plants and other large point sources, such as gas processing plants. In the sustainable development scenario of the latest *World Energy Outlook* of the International Energy Agency (IEA), in which emissions follow a trajectory consistent with the Paris Agreement limiting the increase in global temperature to less than 2°C, CCUS accounts for 16% of the reduction in emissions needed globally in 2040 compared with current levels (International Energy Agency, 2018a). This would require a rapid expansion in the deployment of CCUS, from around 30 million metric tons (MMT) of CO₂ captured per year at present to around 2,300 MMT per year by 2040.

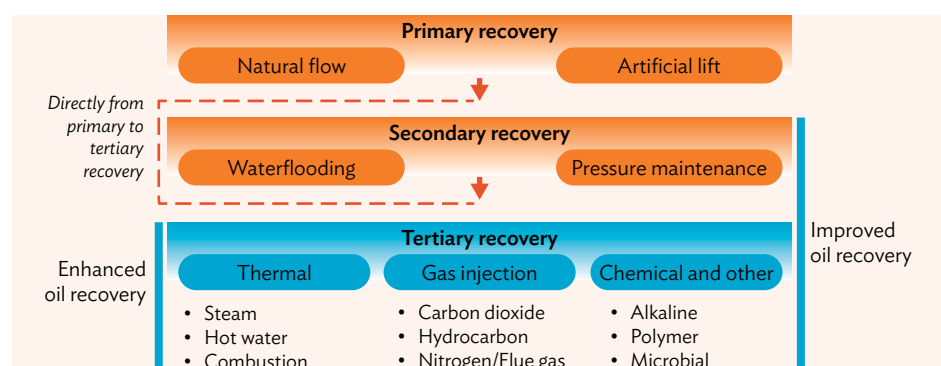
CCUS can also contribute to broader energy security and environmental, societal, and economic goals by:

- (i) enabling greater energy diversity, including the continuing, cleaner use of fossil fuels;
- (ii) maintaining long-term employment and investment opportunities in energy-intensive industries;
- (iii) protecting the value of substantial investments in energy and other industrial infrastructure that have already been made;
- (iv) expanding the choice of technologies for power generation; and
- (v) enabling investment in alternative energy sources and carriers, including low-emission hydrogen production from fossil fuels.

B. Carbon Dioxide-Enhanced Oil Recovery for Producing Oil

CO₂-EOR, involving the injection of CO₂ into oil reservoirs to enhance oil recovery, has been practiced on a commercial scale since 1972, when several natural gas processing plants in the Val Verde area of West Texas began capturing CO₂ to supply EOR operations at nearby mature oilfields. It is the leading type of tertiary oil recovery technique currently in use in the US and worldwide (Figure 1 and Box 1).

Figure 1: Oil Recovery Techniques



Source: G. Kristopher. 2015. Why it's Important to Know the Crude Oil Extraction Process. *Market Realist*. 15 January. <https://marketrealist.com/2015/01/important-know-crude-oil-extraction-process/>.

The limited deployment of CO₂-EOR technology to date reflects various technical and economic constraints. The main factors that determine its feasibility in practice are the geological and petrophysical characteristics of a given reservoir; the physical and chemical characteristics of the oil; the production history, condition, and accessibility of the field; and the availability and cost of CO₂. CO₂-EOR usually involves a miscible process, i.e., mixing of CO₂ with the oil to improve the rate of flow of the oil to the wellbore. As with other EOR techniques, it is usually effective only for light crude oils held in carbonate and sandstone formations. In some cases, another

Box 1: Oil Recovery Techniques

Conventional oilfields typically have three main production phases. In the first phase, oil typically flows unaided to the well under the pressure that exists naturally within the reservoir, but the rate of flow tends to decline over time as extraction of the oil (and water) progressively leads to a decline in pressure. At this point, producers may apply a range of secondary and tertiary techniques to enhance oil recovery and compensate for declining production. Secondary recovery involves the injection of fluids, usually water, into the well to increase pressure and flow rates. Once extracted, the oil and water are easily separated as they are not miscible, i.e., they do not mix. In practice, secondary recovery is often applied at an early stage in the production lifetime of an oilfield, especially if the natural pressure of the reservoir is low.

Tertiary recovery—the third level of production enhancement, commonly referred to as enhanced oil recovery (EOR)—involves the use of techniques that aim to change the properties of the oil or the reservoir rock, or alter flow patterns within the reservoir, to make the oil flow more easily to the well, as well as increase reservoir pressure. This requires injecting into the reservoir a substance that will interact with oil to alter its density or viscosity, reduce the adhesiveness of the rock to the oil (“wettability”) or plug high-permeability flow paths in the reservoir.^a Tertiary methods include thermal recovery (which usually involves injecting steam or hot water into the field), chemical flooding (the injection of a chemical or mixture of chemicals such as alkaline ones or polymers), and the injection of a miscible gas, such as carbon dioxide (CO₂). The choice of recovery technique in each case depends on the characteristics of the reservoir, the degree of depletion, and economic considerations. Gas injection, mainly involving CO₂, accounts for nearly 60% of EOR production in the United States.^b Experience there shows that CO₂-EOR can boost recovery by 5% to 15% of the original oil in place, depending on the miscibility of oil and CO₂.^c

^a International Energy Agency (IEA). 2015. *Storing CO₂ through Enhanced Oil Recovery: Combining EOR with CO₂ Storage (EOR+) for Profit*. Paris: Organisation for Economic Co-operation and Development and IEA.

^b Government of the United States, Department of Energy. 2019. *Enhanced Oil Recovery*. Washington, DC: Office of Fossil Energy. <https://www.energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery>.

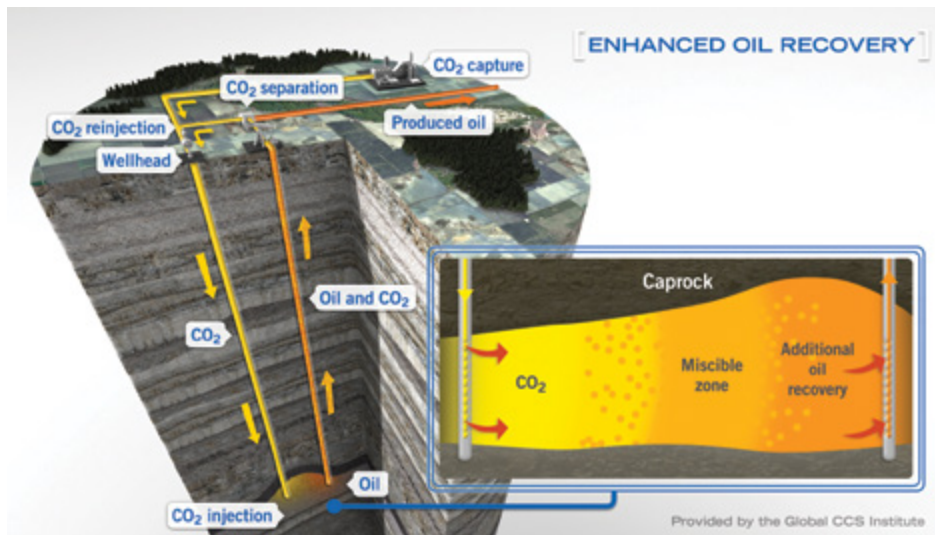
^c IEA. 2013. *Resources to Reserves*. Paris: Organisation for Economic Co-operation and Development and IEA.

Source: Authors.

miscible gas, such as nitrogen and hydrocarbon gases (e.g., propane or butane), may be preferred on technical or economic grounds. The oil price is the single most important determinant of the economics of CO₂-EOR projects, with a higher price typically leading to more investment in new projects and higher rates of CO₂ injection. CO₂-EOR is generally a costlier technique than primary or secondary ones.

In a standard miscible CO₂-EOR process, relatively pure CO₂ (typically at least 95% by volume) is injected into the reservoir and mixes with the oil (Figure 2). Mixing oil and CO₂ has the effect of reducing the capillary forces that trap the oil in the reservoir rock and making it flow more freely to the producing well. Other gases, such as nitrogen and hydrocarbon gases including propane and butane, can also be injected in a similar

Figure 2: Illustration of Carbon Dioxide-Enhanced Oil Recovery



CO₂ = carbon dioxide.

Source: Global CCS Institute. CCS Image Library – Carbon Capture and Storage Images. <https://www.globalccsinstitute.com/resources/ccs-image-library/> (accessed 14 October 2019).

fashion, but CO₂ is often preferred as it mixes with oil at a lower pressure. As a result, CO₂-EOR tends to be more effective in relatively shallow reservoirs, where pressure tends to be lower (International Energy Agency, 2015). CO₂ may also be cheaper.

In a few cases, CO₂ is injected (usually along with water) without any significant mixing with the oil (an immiscible process), typically because the oil is too heavy, to force the oil to the wellbore through pressure in a similar fashion to secondary recovery techniques. Immiscible CO₂ injection or flooding (as it is sometimes called) is generally less efficient than miscible injection at producing oil in terms of the ratio of CO₂ injected and oil produced.

For miscibility to occur, the pressure in the reservoir has to be above the minimum miscibility pressure (MMP)—the pressure at which CO₂ mixes with the oil instead of sweeping it out of the way. The MMP varies according to the type of oil and geology but is typically in excess of 1,500 pounds per square inch for light crude oil (Muslim et al., 2013). Injecting in an alternating fashion slugs of CO₂ and water produced from the reservoir can also enhance miscibility, as the presence of water channels the movement of CO₂ into the tighter parts of the reservoir. This technique, known as “water-alternating-gas,” reduces the need for CO₂ per barrel of oil recovered and, therefore, the cost of procuring CO₂.

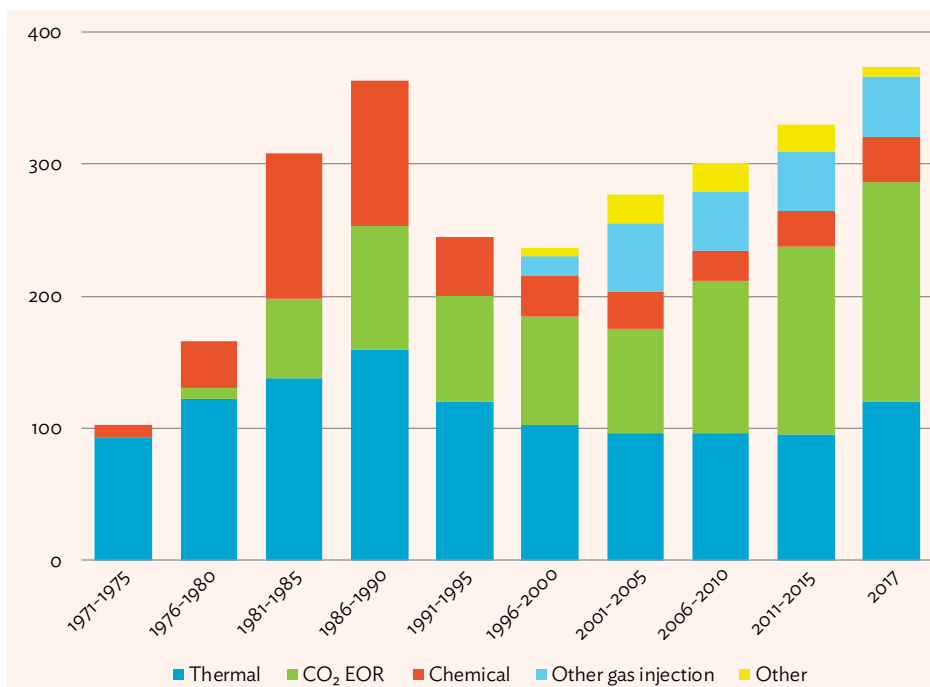
When CO₂ reaches the production wellhead, it is separated from the produced oil so that it can be reinjected (i.e., recycled) to save on the cost of fresh supplies of the gas. CO₂ usually starts to “break through” at production wells relatively soon after the start of injection. Over the life cycle of the EOR project, the CO₂ injection and recovery cycles are repeated many times, with smaller amounts of new CO₂ added

in each cycle as less and less of the gas is retained in the rock. Typically, the injection of one ton of CO₂ yields between two and three barrels of oil (International Energy Agency, 2009).

In principle, CO₂ recycling means that the gas is not released to the atmosphere. Quantitative data on fugitive emissions during handling operations at surface facilities from current CO₂-EOR projects are limited but estimates that do exist suggest that such emissions are minimal. For example, losses have been estimated at less than 0.3% of the total volume of CO₂ injected at the Elk Hills CO₂-EOR project in the US (Hill, Hovorka, and Melzer, 2013).

The contribution of CO₂-EOR to global oil production is relatively small at present but is growing rapidly. In 2017, there were 166 projects in operation around the world, all but 14 of which were in the mid-west US, close to where the technology was first developed and applied. Global output of oil from these projects, almost all of which are onshore, amounted to about 450,000 barrels per day (b/d)—equal to about 0.5% of world output.³ Both the number of projects and output have more than doubled worldwide since the turn of the century (Figure 3).

Figure 3: Number of Enhanced Oil Recovery Projects Worldwide by Type



CO₂-EOR = carbon dioxide-enhanced oil recovery.

Source: C. McGlade, G. Sondak, and M. Han. 2018. Commentary: Whatever Happened to Enhanced Oil Recovery?. *IEA Newsroom*. 28 November. <https://www.iea.org/newsroom/news/2018/november/whatever-happened-to-enhanced-oil-recovery.html>.

³ International Energy Agency (IEA). 2018. World Energy Outlook 2018 – EOR Database. <https://www.iea.org/media/publications/weo/EOR-database-WEO18.xlsx> Organisation for Economic Cooperation and Development/IEA (accessed 14 October 2019).

The particular success of the technology in the US is due to several factors, notably the maturity of the industry, a set of geological and petrophysical characteristics that make mature US fields conducive to CO₂ injection, the availability of inexpensive sources of CO₂ and an extensive CO₂ pipeline system, and a favorable fiscal and legal framework. In 1980, faced with the prospect of declining domestic oil production, the federal government introduced the Crude Oil Windfall Profit Tax, which kick-started the US EOR industry by significantly reducing its tax burden. In 2018, the US tax code section 45Q tax credit was amended to provide a tax reduction of up to \$35 per ton of CO₂ injected for 12 years and permanently stored in EOR operations on the condition that the gas would otherwise be emitted by an industrial facility or power plant (Section V. Next Steps).⁴

Most CO₂ used in US projects today comes from naturally occurring underground reservoirs, though new projects are underway to capture the CO₂ emitted from industrial applications such as natural gas processing, fertilizer, ethanol, and hydrogen plants—either in response to policy incentives or because naturally occurring reservoirs of CO₂ are not close at hand. In fact, one of the earliest large-scale CO₂-EOR projects, at the Weyburn oilfield in Saskatchewan, Canada, which started up in 2000, makes use of anthropogenic CO₂ piped in via a 320-kilometer (km) pipeline from a coal-gasification plant in North Dakota in the US.⁵ The project was expanded to include the adjacent Midale field in 2005.⁶ Since 2014, the Boundary Dam power station in Saskatchewan, Canada also supplies CO₂ to the Weyburn and Midale fields. The Yanchang CCUS project, under construction in the People's Republic of China (PRC), which is supported by ADB, involves the capture of more than 400,000 tons of CO₂ per year from two coal-gasification plants and its use for CO₂-EOR at local oil fields.

C. Carbon Dioxide-Enhanced Oil Recovery as a Means of Storing Carbon

Although the technology was developed solely with the aim of enhancing oil recovery, the use of CO₂-EOR as a means of permanently storing the gas in the ground to mitigate climate change—referred to here as CO₂-EOR+—is attracting interest around the world. It has the potential to significantly reduce overall CO₂ emissions from oil (Box 2). The US Environmental Protection Agency has acknowledged that CO₂ can be safely stored when injected through permitted

⁴ Government of the United States, Office of the Law Revision Counsel. 2019. *26 USC 45Q: Credit for Carbon Oxide Sequestration*. Washington, DC: United States Code. 3 October. <http://uscode.house.gov/view.xhtml?req=%28title:26%20section:45Q%20edition:prelim%29> (accessed 14 October 2019).

⁵ Petroleum Technology Research Centre. Weyburn–Midale: The IEA GHG Weyburn–Midale CO₂ Monitoring and Storage Project. <https://ptrc.ca/projects/past-projects/weyburn-midale>.

⁶ According to the IEA, the Weyburn–Midale EOR project produced 17,100 b/d of incremental oil (over and above what would have been produced without CO₂ injection) in 2017. Earlier data for 2012 show production of 18,000 b/d and an injection rate of around 13,000 tons of CO₂ per day, i.e., about 1.5 barrels of oil per ton of CO₂. Of this gas, 6,500 tons were purchased and 6,500 tons recycled, or approximately 3 barrels per purchased ton of CO₂ (IEA, 2014).

Box 2: How Big Are the Carbon Dioxide Emissions Reductions from Carbon Dioxide-Enhanced Oil Recovery?

Carbon dioxide-enhanced oil recovery (CO₂-EOR+) maximizes storage of carbon dioxide (CO₂), thereby cutting emissions. But it also boosts the production of oil, the majority of which is burned as fuel, resulting in additional emissions. The overall net impact on emissions depends on factors specific to each project and whether the oil produced displaces or supplements oil that would otherwise come from other sources.

At the project level, emissions depend on how much CO₂ is stored, the source of the gas, the permanence of the storage, and how much energy is used in the production process. Energy requirements and their associated emissions relative to conventional production can be substantial because of CO₂ recycling, which involves separation of the gas from the produced liquids and other gases.^a The more CO₂ that is permanently stored in the field, the more that is obtained from anthropogenic sources and the less energy that is used in producing the oil, the bigger the emission savings will be compared with a conventional oil project.

The impact of the oil produced from a CO₂-EOR+ project on the global oil market also affects CO₂ emissions from the use of the oil. If the oil simply replaces that from other projects that do not involve CO₂ storage, those emissions will not change. But if that oil adds to global oil supply, oil prices could fall, boosting demand and leading to higher emissions at the point of use, offsetting at least part of the savings at the project level. For CO₂-EOR+ to be attractive to the operator of the field, the cost of recovering a barrel of oil must be lower than that produced from competing options (other types of EOR at the same field or the development of other resources). Other things being equal, this would be expected to lead to a fall in the price of oil relative to what it would be were the investment in the project not to go ahead. The extent to which this would raise demand and emissions depends on the elasticity of demand for oil and how other suppliers, notably members of the Organization of the Petroleum Exporting Countries respond. For CO₂-EOR+ to lower net emissions, the amount of CO₂ stored would need to exceed the increase in emissions due to lower prices.

In practice, assessing the net impact on emissions requires a quantitative life-cycle assessment, involving modeling of oil market dynamics and taking account of project-specific characteristics. Initial studies that have been carried out suggest that the net emissions savings can be significant. The International Energy Agency (IEA) has calculated that the overall emissions reductions that could be achieved amount to 0.5–1.5 tons of CO₂ per ton injected, depending on the configuration of the project and the type of oil displaced.^b These estimates are underpinned by an assessment that adding very large amounts of CO₂-EOR potential to global oil supply would result in about 0.8 barrels of higher cost oil production being displaced for each barrel produced using CO₂-EOR and 0.2 barrels of additional oil. In all cases, the CO₂ is assumed to come from anthropogenic sources.

Another study using data for the United States (US) industry shows that life-cycle emissions from CO₂-EOR operations are 28% lower than those associated with a conventional oil production when the CO₂ is sourced from a coal-fired power plant.^c The results are broadly in line with those of an earlier study for the US National Energy Technology Laboratory (footnote a). A study of the Boundary Dam project in Saskatchewan in Canada found a reduction in emissions of up to 63%.^d

^a G. Cooney, J. Littlefield, J. Marriott, and T. Skone. 2015. Evaluating the Climate Benefits of CO₂-Enhanced Oil Recovery Using Life Cycle Analysis. *Environmental Science and Technology*. 49 (12). pp. 7491–7500. <https://pubs.acs.org/doi/pdf/10.1021/acs.est.5b00700>.

^b International Energy Agency. 2015. *Storing CO₂ through Enhanced Oil Recovery: Combining EOR with CO₂ Storage (EOR+) for Profit*. Paris: Organisation for Economic Co-operation and Development and IEA.

^c N. Azzolina, W. Peck, J. Hamling, C. Gorecki, S. Ayash, T. Doll, and L. Melzer. 2016. How Green is My Oil? A Detailed Look at Greenhouse Gas Accounting for CO₂-Enhanced Oil Recovery (CO₂-EOR) Sites. *International Journal of Greenhouse Gas Control*. 51. pp. 369–379. <https://www.sciencedirect.com/science/article/pii/S1750583616302985>.

^d A. Manuilova, J. Koiwanit, L. Piewkhaow, M. Wilson, C. Chan, and P. Tontiwachwuthikul. 2014. Life Cycle Assessment of Post-Combustion CO₂ Capture and CO₂-Enhanced Oil Recovery based on Boundary Dam Integrated Carbon Capture and Storage Demonstration Project in Saskatchewan. *Energy Procedia*. 63. pp. 7398–7407.

Source: Authors.

wells for the purpose of oil or gas-related recovery and is, therefore, a valid climate mitigation measure.⁷ CO₂-EOR+ is one of the ways in which oil companies can reduce the emissions intensity of the oil they supply.

At a minimum, CO₂-EOR+ requires the CO₂ to come from an anthropogenic source and to be otherwise emitted to the atmosphere as part of an industrial activity, such as a power station or industrial facility, including natural gas processing (gas extracted from a reservoir often contains significant amounts of CO₂). If the CO₂ comes from a dedicated natural source, as is often the case at present, CO₂-EOR+ is neither beneficial for the climate nor the development of CCS. For a project to qualify as CO₂-EOR+ in practice, it would also require the gas being stored to be properly measured and verified.

The degree to which the injected CO₂ can be permanently retained in the field is crucial to the attractiveness of CO₂-EOR+ as a climate change mitigation measure. A significant portion of the CO₂ in the reservoir usually remains trapped, or “incidentally stored,” due to capillary forces that act to immobilize its movement within pores in the rock and through dissolution in residual oil and water present in the reservoir (Melzer, 2012). For US projects, the share of injected CO₂ left in the reservoir—the retention ratio—is initially close to 100%, but then falls with successive injections to a floor level of between 40% and 60% (Azzolina et al., 2015; Kuuskraa, Leewen, and Wallace, 2011). To maintain pressure and production, the CO₂ retained (stored) in the reservoir must be compensated through injection of additional CO₂ or water. With each recovery cycle, a more or less constant share of the injected CO₂ is eventually retained in the reservoir until a large volume is securely trapped (Azzolina et al., 2015). With recycling of the produced CO₂ at the field same (or at other field in the vicinity) to minimize the cost of buying new supplies of CO₂, virtually all of the injected gas is ultimately stored.

The volume of CO₂ that is stored in this way depends on the properties of the reservoir and the oil it contains, and on operational factors of oil production, including the duration of the injections, well spacing, the relative position of the injection and producing wells, and, in the case of “water-alternating-gas,” the ratio of water to CO₂ used (International Energy Agency, 2015). Reducing the ratio allows more room in the reservoir for CO₂ rather than water to fill the space left by the oil that is produced and, therefore, the amount of CO₂ that can ultimately be stored in the field once production has ceased.

CO₂-EOR always results in a large amount of CO₂ being stored permanently in the field, even if operated in such a way as to maximize oil production without regard to how much CO₂ is stored. But for the technology to function as CO₂-EOR+ and qualify as a genuine climate mitigation measure, several additional activities need to be undertaken before, during, and following CO₂ injection, including additional

⁷ Government of the United States, Environmental Protection Agency. Memorandum to the Regional Water Division Directors regarding the Key Principles in EPA’s Underground Injection Control Program Class VI Rule Related to Transition of Class II Enhanced Oil or Gas Recovery Wells to Class VI. Washington, DC: Office of Ground Water and Drinking Water. 23 April. https://www.epa.gov/sites/production/files/2015-07/documents/class2eorclass6memo_1.pdf.

measurement, reporting, and verification (MRV) activities.⁸ These include the following (Gupta et al., 2016):

- (i) additional site characterization and risk assessment to collect information on geological formations, as well as abandoned wells, to assess the potential for leakage of CO₂ from the reservoir;⁹
- (ii) additional measurement of venting and fugitive emissions from surface processing equipment;
- (iii) enhanced monitoring and surveillance of the field to identify and, if necessary, estimate leakage rates; and
- (iv) changes to abandonment processes, such as more robust sealing off of the well, including the removal of the uppermost components of wells so they can withstand the corrosive effects of CO₂-water mixtures to ensure that the CO₂ is stored permanently in the reservoir and does not leak out over time.

Economic factors affect the extent to which the operator of a CO₂-EOR project seeks to maximize CO₂ storage rather than oil production and to source the CO₂ from anthropogenic rather than natural sources. The additional investment and activities required for the technology to work as CO₂-EOR+ represent an additional cost to the field operator. Changes in the way CO₂ injection facilities are designed and operated to maximize the amount of gas stored may also incur significant additional costs. Similarly, at the end of operations, leaving as much CO₂ as possible in the reservoir rather than maximizing recovery of the gas and reusing it elsewhere before shutting in the wells and abandoning the field would carry a cost.

For operators to opt for anthropogenic sources of CO₂ and to maximize storage of that gas at all stages of the project cycle, they would either need to be given a financial incentive or be forced to do so through regulation (Ward et al., 2018). Incentives can take the form of carbon pricing, which would lower the price of CO₂ supplies to EOR operators by creating an incentive for industrial emitters to capture the gas and seek a means of storing it, or a direct grant or tax credit per ton of CO₂ stored (as is currently the case in the US). To be effective, the incentive needs to be greater than the additional costs associated with CO₂-EOR+ relative to the traditional process. Regulations requiring operators to maximize storage might achieve the same result but carry the risk of deterring investment in new CO₂-EOR+ projects and scaling back ongoing operations by rendering the process less profitable.

⁸ The MRV plan is a vital tool for operators of CO₂-EOR+ projects to proactively manage project risks. It is typically developed in consultation with regulatory authorities and lenders. Primary requirements would be reservoir zone monitoring to adequately track the pressure, temperature, and flow of CO₂. Should leakage signals be detected, the second tier of monitoring for leakage detection and management would be implemented by monitoring above the reservoir zone; and, at the third tier, near-surface and surface monitoring would be carried out.

⁹ The condition of the well cement, casing, and plug determines if a well can sustain hydrostatic pressure and prevent leakage of fluids and gas (Haagsma et al., 2016).

D. Global Status and Prospects for Carbon Dioxide-Enhanced Oil Recovery

CO₂-EOR+ is starting to take off as new projects are designed with the dual goal of boosting oil production and storing the CO₂, usually in response to financial incentives. In most cases, this involves sourcing the CO₂ from an industrial plant with capture facilities rather than a naturally occurring source. In some cases, field operations at existing CO₂-EOR projects that were originally conceived with the sole objective of enhancing oil recovery are being modified to boost storage by modifying the source of the CO₂ or injection operations.

According to the Global CCS Institute, which maintains a database of large-scale integrated facilities,¹⁰ there are currently 14 CO₂-EOR+ projects in operation around the world with total injection capacity of around 35 MMT per year (Global CCS Institute, 2018). Ten of them are located in North America, of which eight are in the US (Table 1). Five of the US projects started after 2009. The Weyburn–Midale project was the first to be subject to an extensive pilot program to monitor and verify

Table 1: Large-Scale Commercial Carbon Dioxide Capture Projects for Carbon Dioxide-Enhanced Oil Recovery

Country	Project	Start date	Cumulative CO ₂ injection (MMT)
Canada	Great Plains Synfuels (Weyburn–Midale)	2000	40
	Boundary Dam (Weyburn–Midale)	2014	2
United States	Terrell (formerly Val Verde)	1970s	20
	Enid	1980s	>10
	Shute Creek	1980s	>50
	Century Plant	2010	3
	Air Products SMR	2013	4
	Lost Cabin	2013	3
	Coffeyville Gasification	2013	2
	Petra Nova	2016	2
Brazil	Lula/ Sapinhoa pre-salt	2013	7
Saudi Arabia	Uthmaniyah (Ghawar)	2015	2
United Arab Emirates	Abu Dhabi CCS	2016	1
People's Republic of China	CNPC–Jilin	2018	1

CCS = carbon capture and storage, CNPC = China National Petroleum Corporation, CO₂ = carbon dioxide, MMT = million metric ton.

Source: Global CCS Institute. 2018. *The Global Status of CCS 2018*. Melbourne. <https://www.globalccsinstitute.com/resources/global-status-report/>.

¹⁰ Defined as involving the capture, transport, and storage of CO₂ at a scale of at least 800,000 metric tons (Mt)/year for a coal-based power plant and 400,000 Mt/year for other emissions-intensive industrial facilities.

the amount of CO₂ being stored (Box 3). The most recent is the installation in 2017 of CO₂ capture technology at the NRG Petra Nova power station in Texas, a combined 374-megawatt coal- and gas-fired plant, allowing the capture of 90% of the plant's emissions, or 1.8 MMT/year.¹¹ The CO₂ is compressed and transported via a 130-km pipeline to the West Ranch Oilfield, where it is used for CO₂-EOR. Oil production at the field was increased by a factor of 13 to 4,000 b/d. The Texas Bureau of Economic Geology has put a monitoring plan in place to keep track of the injection and movement of the CO₂ beneath the surface and in the rock structures at West Ranch. The project is expected to run for 20 years, involving up to 130 injection wells and 130 production wells.

Box 3: The International Energy Agency Greenhouse Gas Research and Development Program's Weyburn–Midale Carbon Dioxide Monitoring and Storage Pilot Project

The Weyburn and Midale oilfields, located in southeast Saskatchewan, Canada, were brought into primary production in 1954. As is common, oil was initially produced from the reservoir without injection of other fluids. After several years of operation, water flooding (a secondary recovery technique) was introduced to maintain production at both fields together with the drilling of additional (infill) wells to reach parts of the reservoir that had not been previously accessed. In October 2000, Cenovus (formerly PanCanadian or EnCana) began injecting carbon dioxide (CO₂) into the Weyburn field to boost oil production. There are now over 100 injection wells. Apache followed suit in 2005, injecting CO₂ into the Midale field. The two fields combined are expected to produce at least 220 million barrels of incremental oil through miscible or near-miscible displacement with CO₂, extending the life of the fields by 2 to 3 decades.

At the start of CO₂ injection, a comprehensive monitoring and verification pilot program was launched by the International Energy Agency Greenhouse Gas (IEAGHG) Research and Development Program. Although monitoring of the stored CO₂ halted in 2012 and the field is now operated as a traditional enhanced oil recovery (EOR) project, it has provided very useful insights into the potential of combining EOR with CO₂ storage activities. Overall, it is estimated that around 40 million metric tons (MMT) of CO₂ will be permanently sequestered over the project's lifespan—30 MMT at Weyburn and 10 MMT at Midale.

Source: B. Hitchon, ed. 2012. *Best Practices for Validating CO₂ Geological Storage: Observations and Guidance from the IEA GHG Weyburn–Midale CO₂ Monitoring Project*. Sherwood Park: Geoscience Publishing.

¹¹ NRG Energy, Inc. Petra Nova: Carbon Capture and the Future of Coal Power. <https://www.nrg.com/case-studies/petra-nova.html>.

Four large-scale CO₂-EOR+ projects have been completed outside of North America:

- (i) *The Lula-Sapinhoa pre-salt oilfield in Brazil*: This is the biggest CO₂-EOR project of any kind in the world and a pioneer in using the technology in ultra-deep water. The project, which started in 2013, has boosted production by 100,000 b/d using CO₂ per year from a nearby offshore gas-processing plant. An estimated 2.5 MMT was injected in 2017 (Global CCS Institute, 2018). The project involves the deepest CO₂ injection well currently operating in the world, at more than 5,000 meters below sea level.
- (ii) *The Uthmaniyah CO₂-EOR demonstration project in Saudi Arabia*: This project, which is being undertaken by Saudi Aramco (the national oil company), is capturing 0.8 MMT per year of CO₂ from the existing Hawiyah natural gas processing plant and injecting it into the Uthmaniyah production unit of the super-giant Ghawar oilfield—the largest in the world.¹² The project involves piloting new technologies to monitor and verify the behavior of CO₂ underground.
- (iii) *The Abu Dhabi CCUS project in the United Arab Emirates*: This is the first fully commercial large-scale CCUS project in the iron and steel industry, having started operation in 2016. Some 0.8 MMT per year of high-purity CO₂ produced as a by-product of the direct reduced iron-making process at the Emirates Steel Industries factory in Mussafah is captured, transported by pipeline, and injected into the Bab and/or Rumaitha fields by the Abu Dhabi National Oil Company for EOR. The project produced around 10,000 b/d of oil in 2017.
- (iv) *The Phase 3 Jilin project in the PRC*: Operated by the China National Petroleum Corporation, the project started up in 2018, injecting 0.6 MMT per year of CO₂ (combined with earlier small-scale demonstration phases, total cumulative injection reached 1.2 MMT in 2018).

In addition to existing CO₂-EOR+ projects, five more commercial large-scale projects are currently under construction and due to be operational by 2020: two in Canada (the Alberta Carbon Trunk Line Sturgeon and Agrum projects), two in the PRC (at Qilu and Yanchang), and one in Norway (the Full Chain CCS facility) (Global CCS Institute, 2018). In addition, a number of countries, including India and Indonesia, are planning CO₂-EOR+ pilot studies.

The long-term potential for CO₂ storage through CO₂-EOR+ is highly uncertain as few studies have been carried out. According to the IEA, the global technical CO₂ storage potential associated with CO₂-EOR+ projects (based on a field-by-field evaluation of suitability and capacity) could be very large, ranging from 60 gigatons (Gt) to 360 Gt of CO₂ between 2015 and 2065 (International Energy Agency, 2015). This equates to 50% to more than three times the CO₂ storage requirement by 2050 in the IEA's Sustainable Development Scenario. In addition, exploiting this potential would raise oil production by up to 375 billion barrels over the period to 2065, roughly three-quarters from onshore fields. This potential is not evenly distributed in the world, with North America, the Middle East, and the Russian Federation accounting

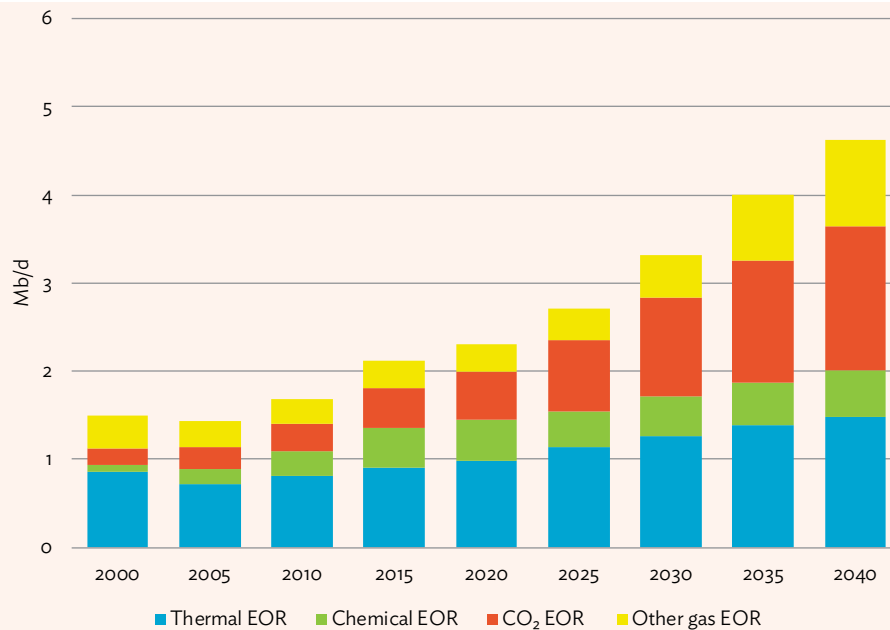
¹² Carbon Sequestration Leadership Forum. Uthmaniyah Carbon Dioxide Enhanced Oil Recovery (CO₂-EOR) Demonstration Project. <https://www.cslforum.org/cslf/Projects/Uthmaniyah>.

for the overwhelming bulk of it, measured by either oil production or CO₂ storage. A more recent study estimates the economic storage potential outside North America at about 40 Gt using currently operating emission sources based on an oil price of \$50/barrel and no penalties for CO₂ emissions (Ward et al., 2018).

Exploiting this potential will depend on a host of economic factors and practical considerations. In many instances, it may not be economically viable to invest in CO₂-EOR+, even where policy incentives or regulations are in place—especially if oil prices remain low. In the near term, another major barrier to investment in the technology outside of North America is an absence of technical capability. CO₂-EOR has become a niche business among American oil and service companies, and the requisite skills, technologies, and expertise are not widely available elsewhere. Half a dozen midsize oil and gas companies currently operate the majority of CO₂-EOR projects in the US (International Energy Agency, 2015). In addition, the deployment of CO₂ capture facilities at industrial plants or power stations is at an early stage. As has proved to be the case with US shale oil and gas drilling, transferring technical capabilities in the field of CO₂ capture and EOR to other regions will inevitably take time.

Despite these barriers, it is widely expected that oil production using CO₂-EOR (including operations that combine long-term storage) will continue to expand over the coming decades. In its latest *World Energy Outlook*, the IEA projects continuing growth in global oil production from CO₂-EOR from 0.46 million barrels of oil per day (Mb/d) in 2015 to 1.64 Mb/d in 2040 in its central scenario (the New Policies Scenario), which takes account of current policies and commitments (Figure 4). CO₂-EOR becomes the leading type of EOR by the 2030s, overtaking thermal techniques (steam flooding). Nonetheless, this represents only a small fraction of the total technical potential.

Figure 4: World Oil Production from Enhanced Oil Recovery by Type in the International Energy Agency's New Policies Scenario



CO₂ = carbon dioxide, EOR = enhanced oil recovery, Mb/d = million barrels of oil per day.

Source: C. McGlade, G. Sondak, and M. Han. 2018. Commentary: Whatever Happened to Enhanced Oil Recovery? *IEA Newsroom*. 28 November. <https://www.iea.org/newsroom/news/2018/november/whatever-happened-to-enhanced-oil-recovery.html>.

III. CLIMATE POLICY IN INDONESIA

A. Trends in Energy Use and Greenhouse Gas Emissions

Indonesia's energy use is likely to continue to grow briskly for the foreseeable future as its economy develops and population expands. Indonesia is currently one of the fastest-growing economies in the world. According to official forecasts, Indonesia's economy is predicted to grow from the 11th largest at present to the 7th largest economy in the world by 2025, with gross domestic product per capita increasing more than six-fold between 2010 and 2050 (Table 2). The population of Indonesia is approaching 250 million—the fourth largest in the world—and is projected to reach 307 million by 2050.

Table 2: Indicators of Economic Development and Energy Use in Indonesia

	2010	2020	2030	2040	2050
Population (millions)	234	252	271	289	307
GDP per capita (\$ per capita)	2,306	3,655	5,823	9,319	14,974
Electrification rate (%)	70	85	99	99	99
Poverty indicator (%)	12	8	3	3	2

GDP = gross domestic product.

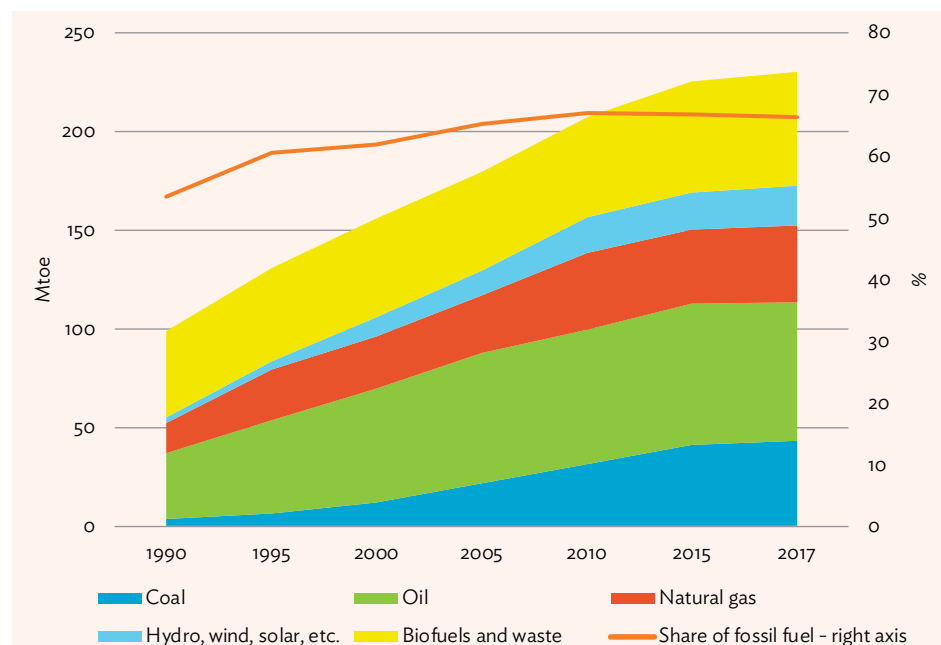
Sources: Government of Indonesia, Ministry of Energy and Mineral Resources of the Republic of Indonesia. 2014. *Indonesia Energy Policy*. Jakarta. <https://eneken.ieej.or.jp/data/5587.pdf>; and Institut Teknologi Bandung (ITB or Bandung Institute of Technology) and LEMIGAS. 2017. *Knowledge Partnership Program: Promoting Carbon Capture and Storage in Indonesia*. Jakarta: ITB/LEMIGAS.

Total primary energy demand has more than doubled since 1995, with most of the increase met by fossil fuels (coal, oil, and natural gas). One reason for this is the limited domestic availability of other fuels for powering the industry and transportation sectors, which account for a major part of the country's energy consumption. Indonesia is well endowed with coal, oil, and gas resources. In 2016, oil was the leading fuel in Indonesia's energy mix, meeting 31% of the country's total needs, followed by biomass (25%), coal (19%), and gas (17%). Geothermal provided 8% and hydropower 1%; the contribution of other renewables was negligible. Coal accounts for well over half of all the power generated in Indonesia.

The fuel mix shifted markedly over the 10 years to 2016, with the share of coal increasing sharply—mainly due to the rapid growth in demand for electricity—and the share of

biomass falling with switching by households to modern forms of energy (Figure 4). The share of oil also fell, while that of gas increased slightly. Overall, the share of fossil fuels has been trending up since the 1990, reaching nearly 67% in 2017, compared with 53% in 1990 (Figure 5).

Figure 5: Historic Trends in Total Primary Energy Supply by Source in Indonesia

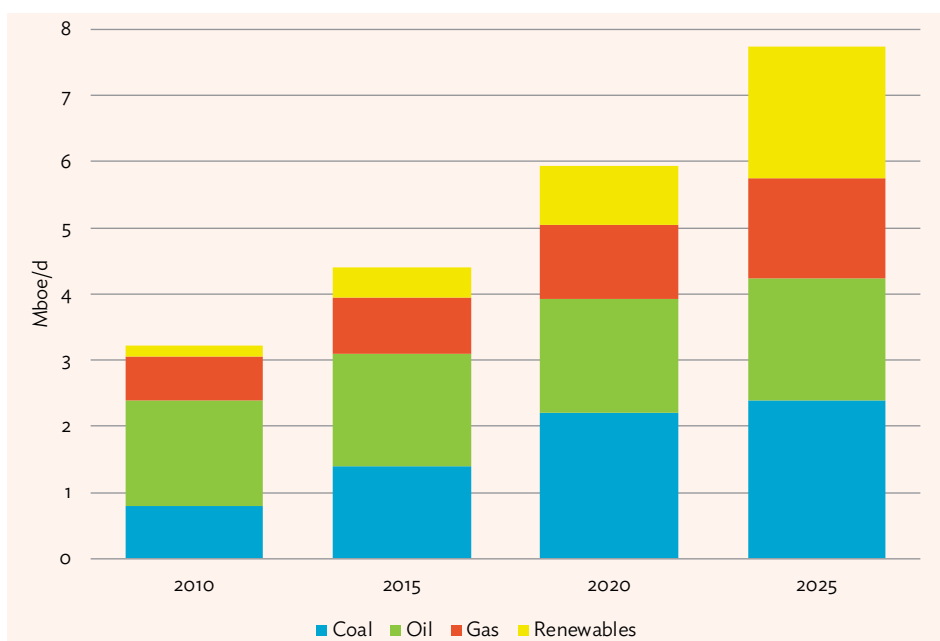


Mtoe = millions of tons of oil equivalent.

Source: International Energy Agency (IEA). Total Primary Energy Supply (TPES) by Source, Indonesia 1990–2017. IEA Statistics. <https://www.iea.org/statistics/> (accessed 14 October 2019).

In the absence of a radical change in government policy, energy use and GHG emissions in Indonesia are expected to continue to grow in the medium term in response to economic and population growth. According to official projections, Indonesia's energy demand, excluding noncommercial biomass, is set to more than double from 3.4 million barrels of oil equivalent per day (Mboe/d) in 2016 to 7.7 Mboe/d by 2025 (Figure 6). A large share of this increase is due to electricity consumption, which is set to continue to grow strongly. Energy needs for electricity generation are set to double between 2018 and 2026, from 290 terawatt-hours (TWh) to 562 TWh (PwC, 2017). Coal and gas are expected to remain the leading fuels in the power sector. The share of renewables, including wind and solar power, is projected to grow significantly, but fossil fuels are likely to continue to meet the bulk of the country's energy needs. Demand for petroleum-based transport fuels is also expected to continue to grow strongly (Badan Pengkajian dan Penerapan Teknologi, 2018).

Figure 6: Projected Total Primary Energy Demand by Source in Indonesia



Mboe/d = million barrels of oil equivalent per day.

Note: Excludes noncommercial biomass.

Sources: For historical data, see Government of Indonesia, Ministry of Energy and Mineral Resources of the Republic of Indonesia (MEMRI). 2018. *Handbook of Energy & Economic Statistics of Indonesia*. Final Edition. Jakarta. <https://www.esdm.go.id/assets/media/content/content-handbook-of-energy-and-economic-statistics-of-indonesia-2018-final-edition.pdf>. For projections, see Government of Indonesia, MEMRI. 2014. *Indonesia Energy Policy*. Jakarta. <https://eneken.ieej.or.jp/data/5587.pdf>.

Continuing strong growth in the use of fossil fuels, led by coal, is set to push up GHG emissions at an even faster rate than energy demand. Indonesia is already the world's sixth-largest emitter of GHGs and the largest contributor of forest-based emissions. Energy use is the single largest source of the country's emissions, accounting for over one-third of the total. According to official projections, annual CO₂ emissions from the energy sector are set to more than double between 2012 and 2025 to over 1.2 Gt, based on a reference scenario that assumes no change in policy (Wijaya et al., 2017).

B. National Climate Mitigation Policy

Given its growing importance in the world, Indonesia's success in meeting its national climate pledges will have a significant impact on future increases in global temperature. The Indonesian government is committed to addressing the impact of climate change by setting emissions reduction targets and devising a plan of action to ensure they are met. In 2010, it voluntarily pledged to reduce its GHG emissions unconditionally by 26% below a business-as-usual scenario by 2020. In its nationally determined contribution (NDC) submitted to the United Nations Framework Convention on Climate Change in 2016, Indonesia committed to reduce its GHG

emissions by 29% below its business-as-usual scenario by 2030 unconditionally and by up to 41% on condition that international support for finance, technology transfer, and capacity building is made available.¹³

The Government of Indonesia has adopted several measures designed to meet the commitments set out in the NDC. In the energy sector, notable recent moves include Government Regulation No. 72/2014 on National Energy Policy, which provides guidance on the development and transformation of Indonesia's energy sector in the face of rising demand for energy services, including a growing role for renewable energy. Subsequently, the government issued the regulation, which sets a target of producing at least 23% of its energy mix from renewable energy (excluding noncommercial biomass) by 2025 and at least 31% by 2050, compared with less than 6% in 2010. It also aims to enhance energy security by reducing reliance on fossil fuels, targeting a fall in the share of the energy mix in 2025 to less than 25% for oil and 30% for coal, while that of gas is targeted to rise to 22%. The targets for 2050 are 20% for oil, 25% for coal, and 24% for gas.

The government has since adopted two major measures to implement the Government Regulation No. 72/2014 on National Energy Policy. In 2016, the Ministry of Energy and Mineral Resources Decision No. 5899/K/20/MEM/2016 on Electricity Supply Business Plan year 2016–2023 was announced, establishing quotas for each type of generating plant to 2025 consistent with the targets set out in the Government Regulation No. 72/2014. And in 2017, the National Energy Plan (Presidential Regulation No. 22/2017 on National Energy Plan) was adopted to serve as reference for national and local governments, state-owned enterprises, and other stakeholders. The plan sets out detailed national and regional targets for each energy subsector and specific actions in end-use sectors, including energy efficiency and conservation measures.¹⁴

The government has emphasized that the country's contribution to meeting the goals of the Paris Agreement should not come at the cost of economic progress in view of the continuing need to address poverty. The Deep Decarbonization Pathways Project of the Institute for Sustainable Development and International Relations and the Sustainable Development Solutions Network proposes that, in Indonesia, priority should be given to cutting the carbon intensity of electricity generation, proposing a targeted reduction of 94% from 871 grams of CO₂ per kilowatt-hour in 2010 to just 50 grams in 2050 (Siagian et al., 2015). This would require a wholesale shift to renewables and natural gas, as well as equipping coal- and gas-fired power plants with carbon capture facilities. The study recognizes that, even with rigorous action to decarbonize the Indonesian economy, emissions will continue to increase until 2030 due to economic development, falling thereafter as a result of decarbonization measures.

¹³ United Nations Framework Convention on Climate Change. 2016. *First Nationally Determined Contribution: Republic of Indonesia*. November. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Indonesia%20First/First%20NDC%20Indonesia_submitted%20to%20UNFCCC%20Set_November%20%202016.pdf.

¹⁴ Government of Indonesia. n.d. *New Paradigm of Indonesia Energy Policy and Planning*. Jakarta: Indonesia National Energy Council. https://www.doe.gov.ph/sites/default/files/pdf/announcements/acd_14_new_paradigm_indonesia_energy_policy_and_planning.pdf.

C. Role of Carbon Capture, Utilization, and Storage in Indonesia's Climate Strategy

CCUS in the form of CO₂-EOR+ is a proven technology that could, in principle, contribute to Indonesia's climate mitigation efforts. Indonesia is a long-standing producer of crude oil, though production has been falling steadily for more than 20 years, having reached a plateau between 1977 and 1995, turning the country into a net oil importer. The government is seeking to boost oil production and reduce import dependence for economic and energy security reasons. There may be extensive opportunities for EOR, including using CO₂, given the maturity of many of the country's oilfields (Section IV. Potential for Carbon Dioxide-Enhanced Oil Reduction in Indonesia). CO₂-EOR+ is a potentially attractive win-win solution for Indonesia, by halting the decline in oil production while addressing the urgent need to curb CO₂ emissions.

Although CCUS has not been formally incorporated into the National Energy Plan, the government is looking at its potential to mitigate CO₂ emissions in the long term. A study carried out for the Indonesian Ministry of Finance in 2015, which evaluated the pros and cons of pursuing deployment of the technology in the country, highlighted the opportunity to leverage global CCUS expertise and the potential to use it to improve coal bed methane production and other supply industries, but flagged concerns about its economic and technical viability, and the lack of any practical experience (Government of Indonesia, Ministry of Finance, 2015). The study recommended pilot testing to confirm the feasibility of storing CO₂; to gain experience and expertise in operating a CCUS project and in measuring and verifying storage via CO₂-EOR+ and other types of CCUS; to learn about the technical challenges, risks, costs, and funding requirements for such projects; and to assess the changes required in the regulatory and fiscal framework to promote large-scale deployment of the technology.

In recognition of the potential for CCUS to contribute to the decarbonization of the Indonesian energy sector, the Directorate General of Oil and Gas within the Ministry of Energy and Mineral Resources of the Republic of Indonesia (MEMRI) set up the Center of Excellence (CoE) for CCS and CCUS in Indonesia in 2017 to help facilitate the implementation of these technologies (Box 4). An initial study highlighted the scope for CCUS, notably CO₂-EOR+, in Indonesia given the extensive potential availability of anthropogenic sources of CO₂ that would otherwise be emitted to the atmosphere, the opportunities for EOR, and the possibility that CO₂-EOR+ could prove to be a low-cost climate mitigation option, where the revenues from enhanced oil production are sufficient to cover the cost of capturing and transporting CO₂ to oilfields (ITB and LEMIGAS, 2017). Some potential pilot projects have already been identified (Section IV).

Box 4: Indonesia's Center of Excellence for Carbon Capture and Storage and/or Carbon Capture, Utilization, and Storage

Indonesia's Center of Excellence (CoE) for carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) was created in 2017 by the director general of oil and gas under the Ministry of Energy and Mineral Resources of the Republic of Indonesia (MEMRI) to promote the collaboration on research and development between the Institut Teknologi Bandung (ITB or Bandung Institute of Technology)—the main Indonesian research institute in the field of CCS—and the Indonesian Research and Development Centre for Oil and Gas Technology (LEMIGAS) with the long-term aim of accelerating CCUS implementation in the country. The CoE has research divisions covering carbon dioxide (CO₂) capture; transportation; storage; well integrity; legal and regulatory matters (with participation from the Ministry of Environment and Forestry); financial analysis; Indonesia's nationally determined contribution (NDC); low-carbon development modeling; health, safety, and environment; risk assessment; risk communication; and measurement, monitoring and verification (with the participation of Pertamina University). Its advisory board includes representatives from government institutions and donor bodies, experts and academics. The steering committee is made up of the heads of the Coordinating Ministry of Economic Affairs, the Coordinating Ministry of Maritime Affairs, MEMRI, the Ministry of Environment and Forestry, SKK MIGAS (the regulator of the upstream oil and gas sector), and Pertamina (the state-owned oil and natural gas corporation).

Achievements to date include:

- (i) the development and launch of an online knowledge portal;
- (ii) a report on membrane-based CO₂ capture technologies and a roadmap for their deployment;
- (iii) a report on CO₂ capture using potassium carbonate solvent with a boric acid promotor;
- (iv) a draft regulation for CCS operations;
- (v) a study on the potential contribution of CCS to Indonesia's NDC;
- (vi) the organization of an annual knowledge workshop; and
- (vii) technical inputs to CCUS pilot projects using CO₂ from natural gas processing plants.

Source: Authors.

IV. POTENTIAL FOR CARBON DIOXIDE-ENHANCED OIL RECOVERY IN INDONESIA

A. Potential for Enhancing Crude Oil Production

Indonesia's oil industry is one of the oldest in the world, with commercial production beginning in 1885. About 75% of exploration and production is located in Western Indonesia, with production concentrated in Sumatra, the Java Sea, East Kalimantan, and Natuna. There are around 60 sedimentary basins across the country, including 36 in Western Indonesia that have already been thoroughly explored; 14 of these are producing oil and gas (PwC, 2018). In underexplored areas of Eastern Indonesia, 39 tertiary and pre-tertiary basins may contain commercial quantities of hydrocarbons.

Oil production peaked in 1977 at over 1.6 Mb/d and has been declining steadily since the mid-1990s. Crude oil production averaged just over 800,000 b/d in 2017, down from 950,000 b/d in 2007. On a net basis, the country exported 53,000 b/d of crude oil in 2007 but imported 107,000 b/d by 2017—equal to around 12% of the country's consumption (Government of Indonesia, MEMRI, 2018b). Natural gas production has also been declining in recent years with the depletion of mature fields.

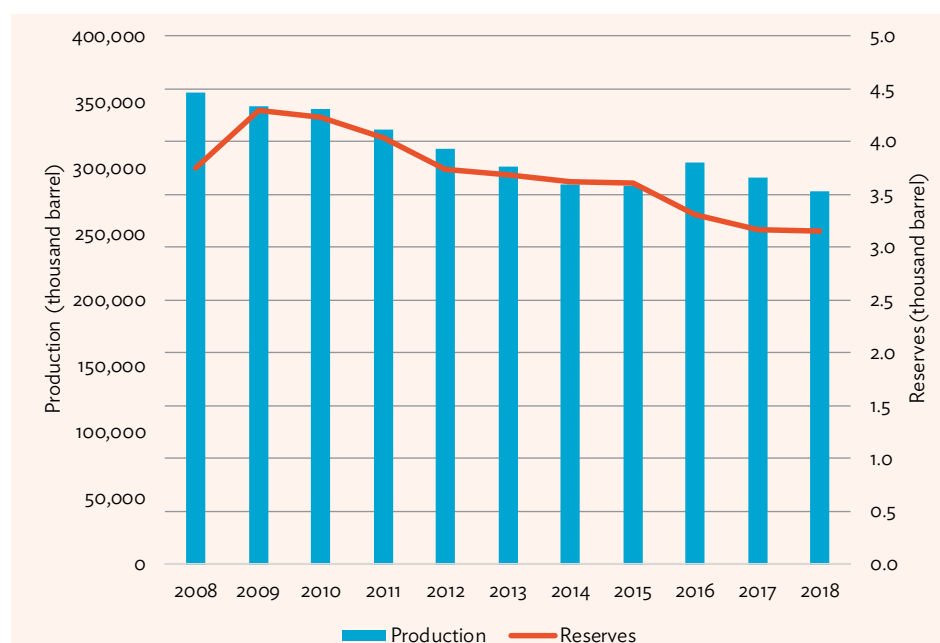
Proven oil reserves have been declining since 2008, from 5 billion barrels to 3.2 billion barrels in 2017 (Figure 7). The reserve replacement ratio (the share of the oil produced each year that is replaced with new reserves) has slipped to around 60% (Rukmana, 2017). This is the result of the natural depletion of mature fields, which continue to account for the vast bulk of output, and a lack of investment, both in exploring for and developing new fields, and in applying secondary and tertiary recovery methods at existing fields.¹⁵ Deliberate cutbacks as required by the production sharing agreements of the Organization of the Petroleum Exporting Countries, of which Indonesia is a founding member,¹⁶ have also contributed to the recent slide in output. The recovery in international oil prices since 2016 may stimulate a modest recovery in upstream oil and gas investment in the near term.

The government is seeking to boost investment in the upstream sector to reverse the decline in production. It has declared several new strategic upstream oil and gas projects, such as the Jangkrik field development, Tangguh Train-3, the Indonesia Deepwater Development Project, and Genting's Kasuri block (PwC, 2017). It is also trying to encourage foreign investment in the upstream industry. It is looking at further changes in the new

¹⁵ The majority of Indonesian fields today have a water cut (the share of water in the total liquids produced) above 80% and, in some cases, as much as 99%; 94% of them are considered mature (Abdurrahman et al., 2017).

¹⁶ Indonesia suspended its membership in 2008 in response to falling production but rejoined in 2015.

Figure 7: Remaining Proven Oil Reserves and Production in Indonesia



Source: Government of Indonesia, Ministry of Energy and Mineral Resources of the Republic of Indonesia. 2018. *Handbook of Energy & Economic Statistics of Indonesia*. Final Edition. Jakarta. <https://www.esdm.go.id/assets/media/content/content-handbook-of-energy-and-economic-statistics-of-indonesia-2018-final-edition.pdf>.

model adopted in early 2017 based on sharing gross production between the state and operators, as the licensing round launched in February 2018 resulted in only four of the 24 blocks on offer being awarded (International Energy Agency, 2018b). Attention is also being given to boosting existing technically recoverable reserves via infill wells and revitalizing production from mature wells by stepping up the use of secondary and tertiary recovery techniques. The Government of Indonesia has been encouraging oil companies operating in the country to use EOR (Abdurrahman et al., 2017).

In principle, many mature oilfields offer the potential for incremental oil production through EOR, including CO₂-EOR, which has not yet been deployed in Indonesia (ADB, 2013). The only experience Indonesia has with EOR of any kind on a commercial scale is steam flooding, which has been used for more than 30 years at the Duri oilfield—the largest project of its kind in the world.¹⁷ Chemical flooding using a combination of alkaline, surfactant, and polymers has also been piloted at three oilfields. Assuming that EOR methods are able to boost the recovery rate (the share of total resources originally in place that is producible) by 5% to 10%, their implementation could lead to additional oil recovery of between 2.5 billion barrels

¹⁷ A chemical EOR pilot project was launched at the Duri field in 1975 but was not successful. Various other chemical pilot projects have been tested at other fields, including at Minas in 2013 and more recently at the Kaji and Semoga and the Meruap and Tanjung fields (Rukmana, 2017). In addition to these pilots, several laboratory and simulation studies were conducted or are currently underway in fields such as Handil and Limau. The first pilot gas injection EOR project, involving the reinjection of natural gas back into the reservoir, was successfully implemented in the Handil field in 1995 and has been underway since.

and 5.0 billion barrels (Abdurrahman et al., 2017). Most Indonesian crude oil is medium-to-light, which is amenable to CO₂-EOR, though—as in other countries—the economics are highly dependent on the oil price and local factors, including the intrinsic characteristics of the reservoirs and the availability and cost of procuring CO₂ (Muslim et al., 2013).

B. Availability of Anthropogenic Carbon Dioxide

The main potential sources of anthropogenic CO₂ in Indonesia are natural gas and associated oil and gas processing plants, and industrial processes that involve the conversion of hydrocarbons, such as power stations and petrochemical plants, including fertilizer factories (Map 1). The gross output capacity from these sources combined throughout the country is estimated to be 6.8 billion cubic feet per day, or about 145 MMT per year (Putra, 2016). Power plants account for the bulk of this capacity (Table 3). All of the CO₂ from these sources is currently released to the atmosphere.

Table 3: Anthropogenic Sources of Carbon Dioxide in Indonesia

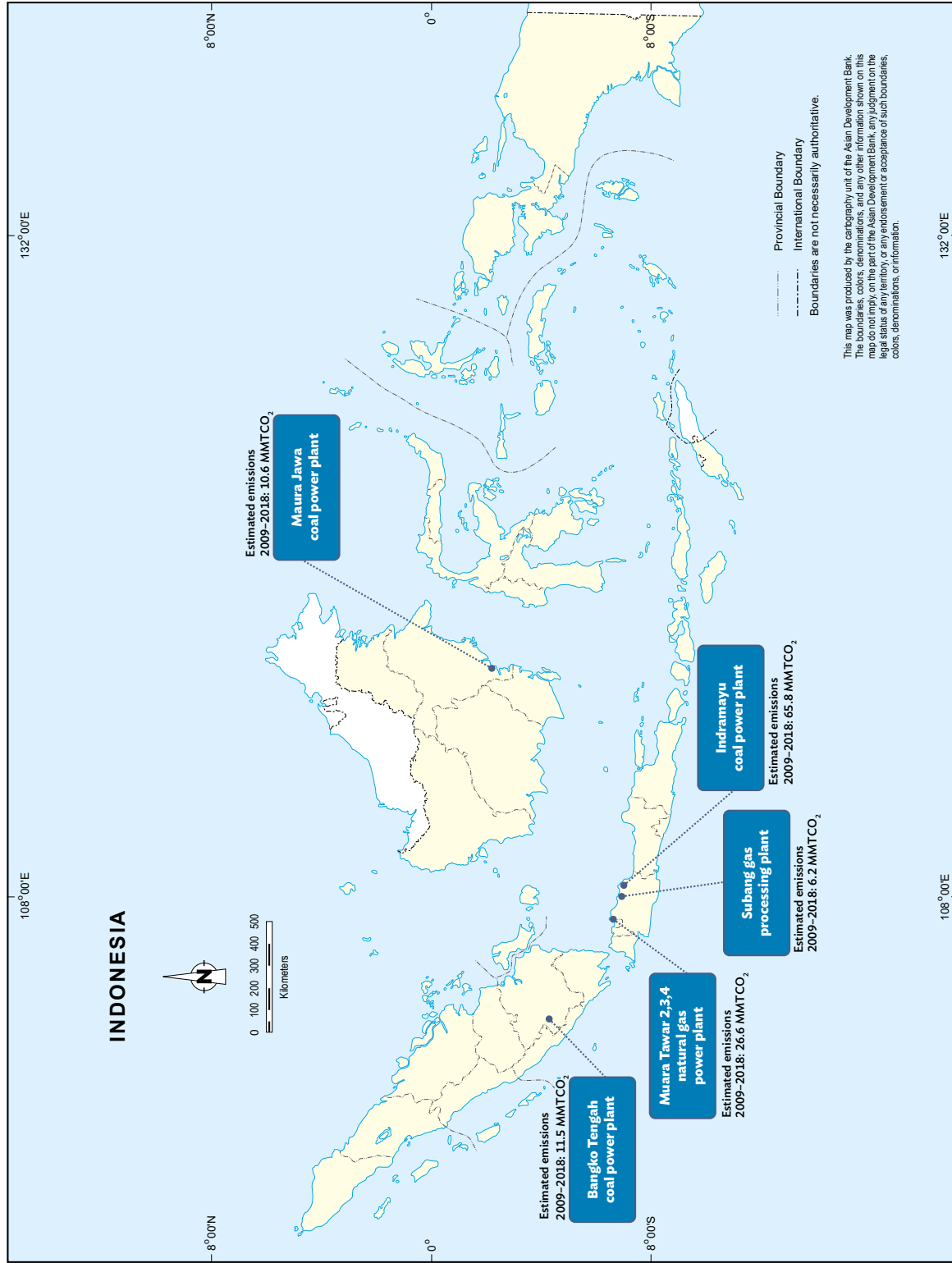
Source	Estimated emissions (MMT/year)	Examples
Natural gas processing	2.8	Subang, Merbau, Cilamaya, Gundih, JTB
Oil and LNG processing	17.3	LNG: Arun, Badak, Tangguh Refineries: Sungai Paknik, Cilacap, Balikpapan, Balongan
Power plants	115.0	Bangko Tengah, Muara Tawar, Indramayu, Muara Jawa
Chemical plants	No estimate available	Fertilizer plants: ASEAN & PIM, Pusri, Kujang, Kaltim Methanol plants: Bunyu Petrochemicals: Gresik Olefin centre: UP.IV Pertamina Cilacap Polypropylene: UP.III Pertamina Plaju Purified terephthalate acid: UP.III Pertamina Plaju
Flared gas	7.9	Offshore gas blocks

ASEAN = PT Asean Aceh Fertilizer (AAF), JTB = Jambaran-Tiung-Biru gas fields, LNG = liquified natural gas, MMT = million metric ton, PIM = PT Pupuk Iskander Muda, UP.III = Unit Pengeloaan III (Development Unit III), UP.IV = Unit Pengeloaan IV (Development Unit IV).

Source: Battelle analysis based on Muslim et al. 2013. *Opportunities and Challenges of CO₂ Flooding in Indonesia*. Paper presented at the Society of Petroleum Engineers Asia Pacific Oil and Gas Conference and Exhibition. Jakarta. 23–24 October. https://www.academia.edu/10778808/Opportunities_and_Challenges_of_CO2-EOR_in_Indonesia.

The processing of natural gas is likely to be the cheapest source of high-purity CO₂ now and in the future. The CO₂ has to be removed before natural gas can be distributed and consumed, so that the only additional costs are purifying and transporting it to the oilfield for injection. Emissions from such plants, including the

Map 1: Large Anthropogenic Sources of Carbon Dioxide in Indonesia



CO₂ = carbon dioxide, MMT = million metric ton.

Note: Emissions cover 2009–2018.

Source: Indonesia CCS Working Group. 2009. *Understanding Carbon Capture and Storage Potential in Indonesia*. Joint Cooperation between the United Kingdom CCS Research Centre and the Government of Indonesia on Strategic Programme Fund. Jakarta. https://ukccsrc.ac.uk/publication_ccs_repo/understanding-carbon-capture-and-storage-potential-in-indonesia/.

large Cilamaya, Gundih, Merbau, and Subang facilities, currently amount to around 2.8 MMT/year. A gas-processing plant at the Jambaran–Tiung–Biru field, construction of which is underway, could provide another 2 MMT/year. The availability of CO₂ from gas processing is likely to grow as several of the gas fields that are expected to come on stream in the coming years have particularly high CO₂ content. One example is the East Natuna field—a large, as yet undeveloped, gas field located offshore north of the island of Natuna.¹⁸

The processing of natural gas used to produce liquefied natural gas and the processing of crude oil in refineries represent an additional potential source of low-cost CO₂ that would otherwise be emitted. The total amount of CO₂ available from these sources is estimated at over 17 MMT/year. Around 8 MMT/year of CO₂ contained in natural gas that is currently being flared could also be used for CO₂-EOR+. The cost of capturing and supplying CO₂ from other sources, especially power plants, where dedicated capture facilities would need to be installed, is likely to be much higher as the concentration of CO₂ in flue gases is generally much lower, except where separation and compression form a necessary part of the industrial process.

C. Candidate Oilfields for Carbon Dioxide-Enhanced Oil Recovery Projects

Identifying candidate oilfields for deploying CO₂-EOR+ in Indonesia needs to take account of both economic and technical considerations. The maturity of most of Indonesia's oilfields and the large amount of oil remaining in them suggest that there is significant technical potential, though the economic potential is likely to be far smaller, especially at low oil prices. As in other parts of the world, the economic viability of CO₂-EOR+ in Indonesia is also likely to hinge critically on the cost of procuring the CO₂, which, in turn, depends on the distance over which it needs to be transported (as well as the volumes involved and the cost of capture). The closer the source of low-cost CO₂, the more attractive such an investment will be. It follows, therefore, that the most promising candidates for CO₂-EOR+ projects are mature fields with declining production that are located in close vicinity to low-cost sources of CO₂, such as natural gas processing plants.

Sumatra appears to be one of the most promising basins for CO₂-EOR+, notably the southern part (ADB, 2013; Putra, 2016; ITB and LEMIGAS, 2017). In addition to the large number of partially depleted oil and gas fields in the region and the existence of major gas-processing plants, South Sumatra has a low population density compared with the rest of the country, well-developed transportation infrastructure, and a relatively stable geology, being distant from seismic and tectonic activity.¹⁹ In its 2013

¹⁸ The field was discovered in 1973, but the high CO₂ content of the natural gas has so far prevented development of the field. In 2011, an agreement to develop the field was signed between Pertamina (the largest investor), ExxonMobil, Total, and Petronas (later replaced by PTT Exploration and Production), but negotiations over a production sharing contract failed. ExxonMobil and PTT pulled out of the consortium in 2017.

¹⁹ Government of Indonesia, MEMRI. 2018. *Current Status and Future Path of Developments for CCUS in Indonesia*. Jakarta: LEMIGAS Research and Development for Oil and Gas. 8 June. <https://d2ocoihd6a5bt.cloudfront.net/wp-content/uploads/sites/837/2018/06/Usman-Pasarai-Current-Status-and-Future-Path-of-Developments-for-CCUS-in-Indonesia.pdf>.

study of the potential for CCS in Indonesia, ADB estimated that nearly 90 MMT of CO₂ could be stored in oilfields and 830 MMT of capacity in gas fields in South Sumatra, many of these fields offering opportunities for CO₂-EOR+ (ADB, 2013).²⁰ It recommended pursuing a pilot project based on captured CO₂ from a gas-processing plant matched with storage in a nearby oilfield. LEMIGAS estimates that the total storage capacity in oil and gas fields amounts to nearly 485 MMT in the Sumatra basins (north, central, and south), compared with 106 MMT in the Java basin and 130 MMT in the Kutai basin (Map 2). It reckons that CO₂-EOR+ could boost oil reserves in South Sumatra by as much as 480 million barrels and store around 75 MMT of CO₂. Nationally, additional oil reserves could amount to 2 billion barrels with associated CO₂ storage of 300 million tons (footnote 19).

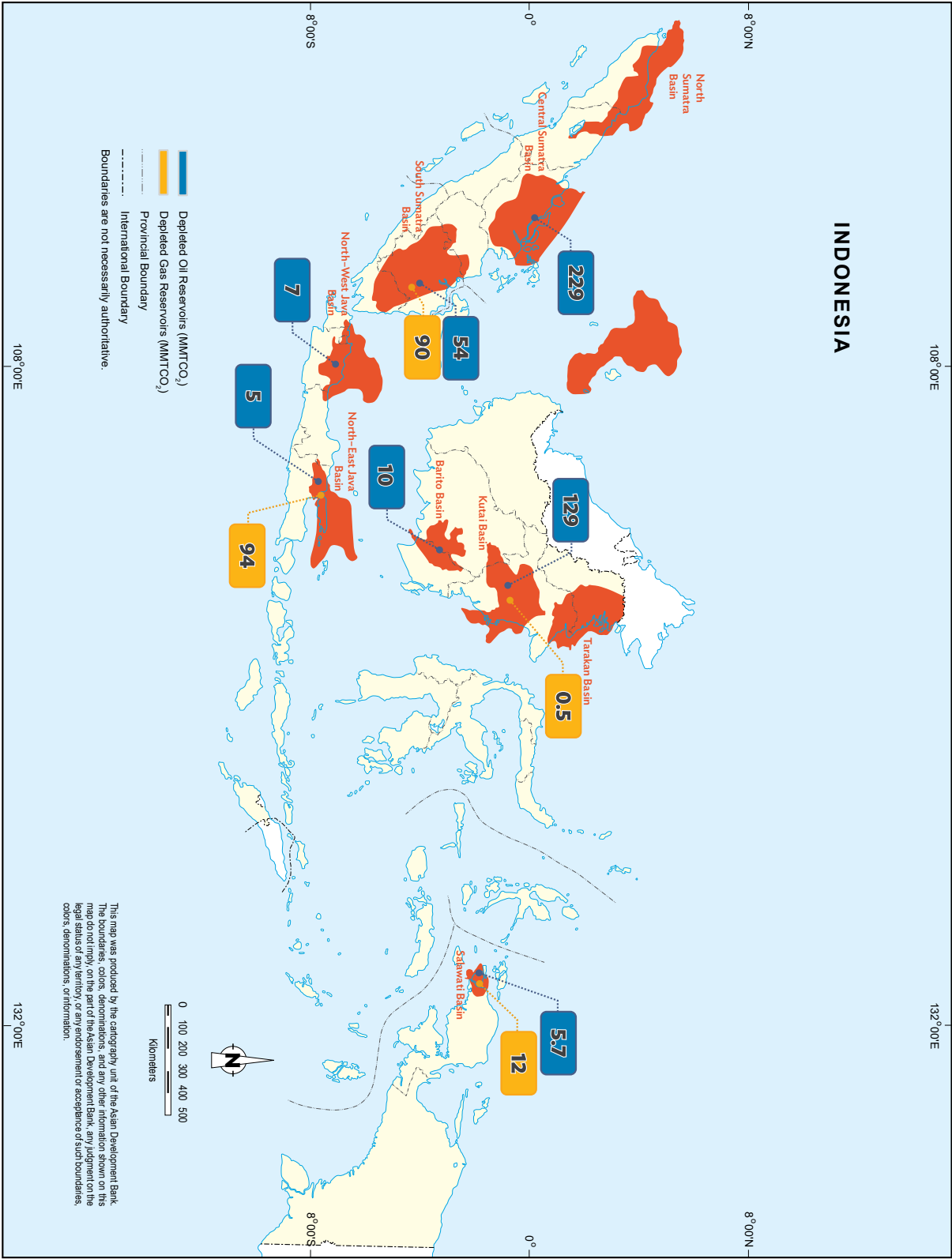
Preliminary studies have already been conducted to evaluate the feasibility of CCUS and to identify potentially suitable sites, linking sources of CO₂ to specific oilfields and other sinks. One such study carried out by LEMIGAS paired potential candidate fields for CO₂-EOR+ with CO₂ sources by drawing 150-km and 300-km circles around the most promising sources and ranking the candidate fields by proximity and by their infrastructure (Putra, 2016). Based on this analysis, it is calculated that close to 1 billion barrels could be recovered from 22 fields using CO₂-EOR+, with around 50 MMT of CO₂ injected each year (Table 4). Most of the CO₂ would come from coal-fired power stations, including up to 11 MMT/year of CO₂ from the Bangko Tengah Power Plant in South Sumatra. In addition, the huge East Natuna gas field (not included in this analysis as it has yet to obtain the green light for development) could provide 40 MMT/year; the primary candidate for use of this gas for CO₂-EOR+ is the Seria field in onshore Brunei. This field has an estimated 2 billion barrels of oil in place, about half of which has been extracted to date, with the potential for additional recovery, with EOR, of around 500 million barrels.

More recently, the CoE has also evaluated Indonesian sedimentary basins for the suitability of deploying CO₂-EOR+ (ITB and LEMIGAS, 2017). The results indicate that there is a priori a significant opportunity to boost oil production while storing large amounts of CO₂ in the reservoirs. Scoring criteria were developed to rank oilfields based on their geological setting, petro-physical characteristics, reservoir rock and fluid properties, and CO₂ storage availability. On this basis, the Kutei, South Sumatra and Central Sumatra basins were found to be the most suitable for a pilot project.

Owing to its large storage potential, the Kutai basin was selected for more detailed evaluation of the feasibility of CO₂-EOR based on standard technical criteria developed by Taber (1997). The evaluation was then narrowed down to the Attaka, Bekapai, and Handil fields (the three largest in the basin), which were subject to reservoir engineering analyses to simulate the impact of CO₂ and water injection on oil recovery (Table 5). The total CO₂ storage potential in those three fields is estimated at over 350 MMT. Pertamina has also carried out laboratory and simulation CO₂ injection studies of the Jatibarang, Gemah, and Beringin fields (Rukmana, 2017).

²⁰ An additional 7.6 Gt of captured CO₂ could be stored in saline reservoirs and 2.7 Gt in coal beds.

Map 2: Carbon Dioxide Storage Capacity of the South Sumatra and the East Kalimantan Basins in Indonesia



MMTCO₂ = million metric ton of carbon dioxide.

Source: LEMIGAS, 2018. *The Latest Status of CCS in Indonesia*. Jakarta. http://www.ccop.or.th/ccsm/data/7/docs/Indonesia_LEMIGAS.pdf.

Table 4: Pairing of Carbon Dioxide Sources and Candidate Oilfields for Carbon Dioxide Enhanced Oil Recovery in Indonesia

Basin	Sources of CO ₂	CO ₂ availability (MMT/year)	Candidate oilfields for EOR	Oil originally in place (million barrels) ^a	Expected recovery with EOR (million barrels) ^b
South Sumatra	Bangko Tengah Power Plant, Associated gas from Jabung Blocks (corridor wells), and Lematang Block (Singa and Harimau fields)	14	Ramba, Kenali Asam, Tempino, Raja, Niru, Abab, Limau Tengah, G. Kemala, Tanjung Tiga, Bajubang, Meruap, Kluang, Beringin	2,200	550
West Java	Muara Tawar Power Plant, Subang Gas Processing Plant	33	Jatibarang, X-Ray, Tambun, Cemara, Tugu Barat A	1,200	300
East Java	Gundih Natural Gas Processing Plant	0.2	Mudi, Sukowati, Kawengan, Nblobo	860	215

CO₂ = carbon dioxide, EOR = enhanced oil recovery, MMT = million metric ton.

^a The total amount of oil contained in the oilfield before the start of production.

^b Assumed to be 25% of the oil in place based on a combined primary and secondary recovery rate of 35% and an ultimate recovery rate after EOR of 60%.

Source: Battelle analysis based on E. Putra. 2016. *Evaluation of CO₂-EOR Injection and Its Potential Application to Indonesia*. Houston: Enerproco. <http://siephouston.org/wp-content/uploads/2017/06/CO2-EOR-SIEPH-Putra.pdf>.

Table 5: Evaluation of Carbon Dioxide-Enhanced Oil Recovery Potential at Oilfields in the Kutai Basin in East Kalimantan, Indonesia

Field	Oil originally in place (million barrels)	Injection rate (tons/day)	Injection period (years)	Primary production (million barrels)	EOR production (million barrels)	CO ₂ used/stored (MMT)
Attaka	1,536	15,940	26.0	373	316	150
Handil	1,457	22,110	20.0	884	351	159
Bekpai	324	19,950	4.5	161	70	33

CO₂ = carbon dioxide, EOR = enhanced oil recovery, MMT = million metric ton.

Source: Institut Teknologi Bandung (ITB or Bandung Institute of Technology) and LEMIGAS. 2017. *Knowledge Partnership Program: Promoting Carbon Capture and Storage in Indonesia*. Jakarta: ITB/LEMIGAS.

LEMIGAS subsequently identified the Beringin field, operated by Pertamina, in southern Sumatra with CO₂ supplied from the company's nearby Merbau gas processing plant (gas gathering station) as another candidate for a pilot CO₂-EOR+ project.²¹ The cost of procuring the CO₂ and Pertamina's interest in pursuing CO₂-EOR were factors in this decision. The project would make use of the CO₂ currently produced at the gas processing plant at Merbau. The plant has a single processing train, which separated out 28,800 tons (79 tons/day) of almost pure CO₂ in 2016.²² All of the CO₂ is currently vented to the atmosphere. The pilot project envisages that 75 tons/day of this CO₂ would be liquefied/chilled and then transported by road tanker to the Beringin oilfield located 65 km away. Existing wells at the field would be modified to create one injection well and four producing wells. It is envisaged that injection would last for 5 years, boosting the recovery factor at the field by 1.4 percentage points to around 3.4% and yielding around 53,000 extra barrels of oil. The process would be immiscible (i.e., not involving any mixing of the CO₂ and oil), as the pressure in the reservoir is not high enough and the oil too heavy to permit any significant degree of miscibility. After 5 years, it is estimated that around 90,000 tons of CO₂ would be retained (stored) in the field.

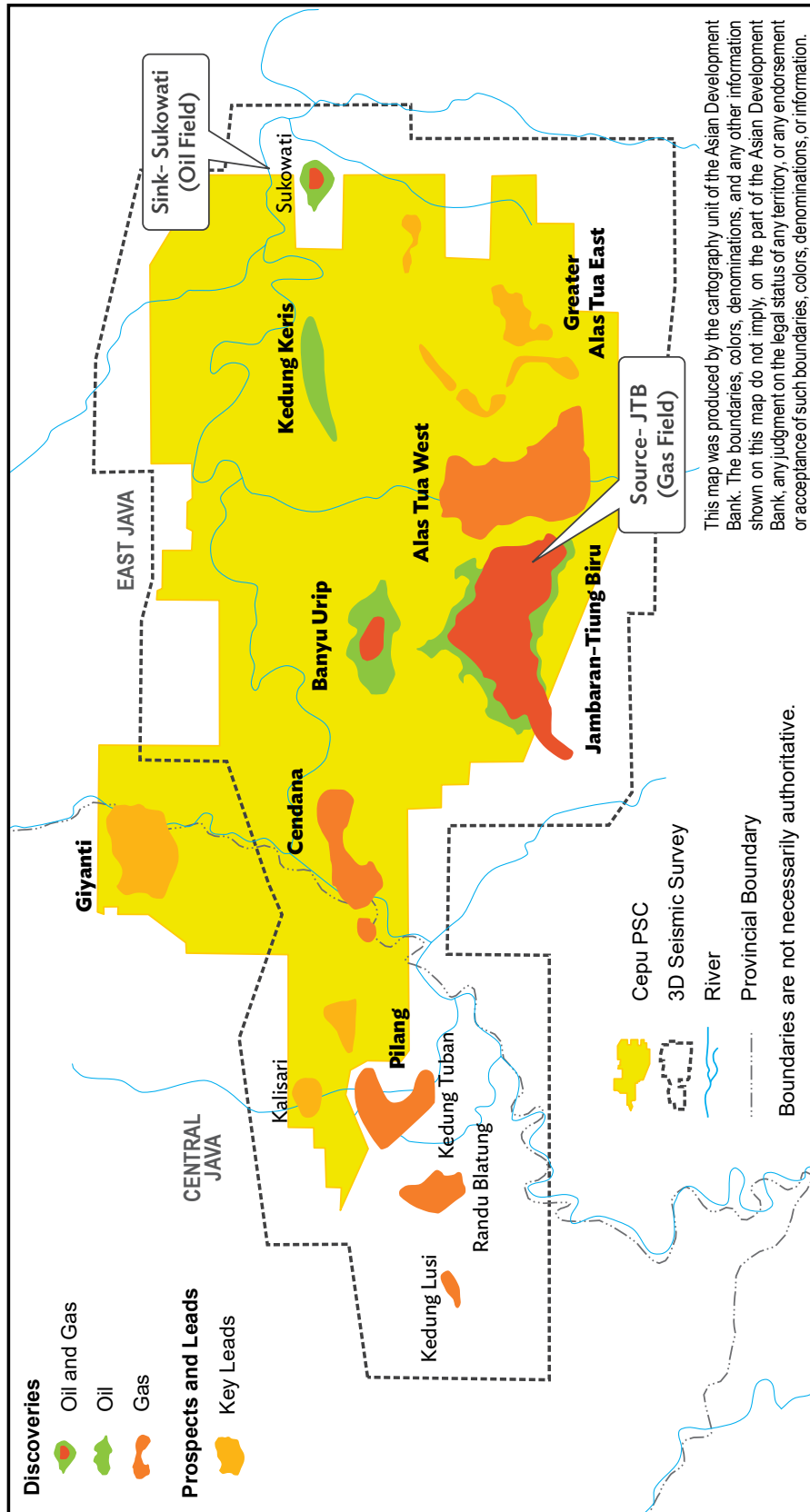
At the end of 2018, LEMIGAS decided to focus its efforts on supporting a pilot project at the Sukowati oilfield located in East Java (Map 3) due its greater potential for full-scale commercial application. The Sukowati field has been in production decline for several years, reaching around 9,000 b/d at present—down from a peak of 46,137 b/d in 2011. Associated gas production is running at 13 million cubic feet per day—less than half its historic peak in 2011. The current recovery factor from the field is about 39%. Around 219,000 b/d of water is currently being injected into the field to boost production. ADB is providing technical assistance to Pertamina EOR—the owner and operator of the field—and the CoE to support the development of the proposed pilot project. Pertamina conducted a full field-scale pre-feasibility evaluation of the project in 2016. Battelle subsequently carried out a review of the pilot project on behalf of ADB based on information provided by Pertamina and its associates, which broadly confirmed the technical and economic viability of the project and identified the need for further action in key areas (Section V. Next Steps).

The Sukowati pilot project consists of a total of five existing wells: four production wells spaced out in the form of a square and a fifth (currently not in production) that would be converted to a CO₂ injection well. Like the Beringin project, the process would be immiscible as the current reservoir pressure is below the minimum miscibility pressure (MMP) and the producing area is not confined such that the injected CO₂ and the accompanying pressure plume (pocket of gas) are able to migrate away from the producing wells. If the pilot proves to be successful, a commercial-scale project using a miscible process could be deployed, involving the use of all 35 existing production wells and drilling new CO₂ and water injection wells. All of the CO₂ for the pilot project would be sourced from the Sukowati field itself; the

²¹ LEMIGAS has proposed another pilot project involving dedicated storage (with no CO₂-EOR). It plans to capture 20,000 tons of CO₂ from the natural gas processing plant at Gundih in Central Java and inject and store it in the nearby Ngrayong sandstone formation. Injection would last for 2 years followed by a period of monitoring.

²² The removal of CO₂ takes place in an absorber column by using a multi-stage proprietary A-MDEA (Active Methyl Diethanol Amine) process, producing a CO₂ stream with a purity of 99.9% (footnote 19).

Map 3: Location of Sukowati and Jambaran-Tiung-Biru Carbon Dioxide-Enhanced Oil Recovery Pilot Project



Source: Pertamina. 2018. *Carbon Dioxide-Enhanced Oil Recovery Project at Sukowati Field*. Presentation slides during the Asian Development Bank; Center of Excellence (CoE) for Carbon Capture and Storage (CCS) and Carbon Capture, Utilization, and Storage (CCUS); LEMIGAS; and CoE Institut Teknologi Bandung (ITB, Bandung Institute of Technology) Sukowati CCUS Enhancement First Review Meeting. Jakarta. 4 December.

associated gas currently extracted from the field contains about 40% CO₂ (around 5 million standard cubic feet per day [mmscf/d], or 95,000 tons per year), which is stripped from the gas before sales. Additional gas that would be needed for the field-scale project (up to 95 mmscf/d or 1.8 MMT/year) would come from the nearby JTB gas-processing plant currently under construction—the largest of several potential sources of anthropogenic CO₂ in the area.

Pertamina estimates that the full field-scale deployment of CO₂-EOR would increase oil recovery from the field by an additional 50 million barrels, raising the recovery rate by 16.8 percentage points. It is estimated that the field is capable of storing up to 1,260 MMT. A project involving the highest proposed rate of injection (100 mmscf/d, or 1.9 MMT/year) would require an estimated \$440 million of capital expenditure and \$797 million of operating expenditures over an assumed project lifetime of 15 years.

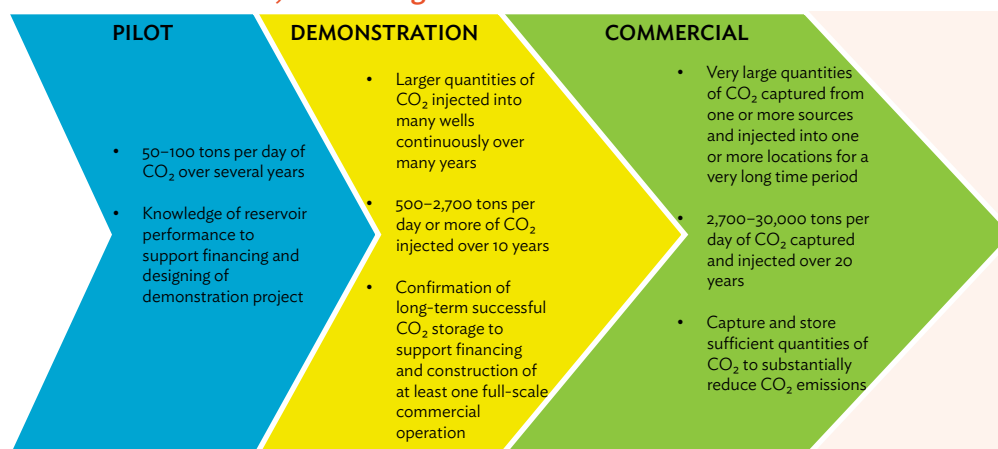
V. NEXT STEPS

A. Pilot Studies and Demonstration Projects

The critical first step in the process of developing CO₂-EOR+ in Indonesia is to launch an initial pilot project. Commercial projects will only follow if at least one pilot and demonstration project has been operating successfully for several years. Such projects will require detailed design, cost estimates, and business plans, as well as environmental impact assessments. The learning and experiences from the pilot and demonstration projects will be of enormous value in helping operators prepare these inputs. ADB has previously proposed a generic road map for the development of CCUS generally, applicable to Indonesia and three other Southeast Asian countries that were selected for study (the Philippines, Thailand, and Viet Nam), stretching over 15 years (ADB, 2013). It includes a timeline for all activities relating to project development (Figure 8).

Pilot projects, which typically would be expected to involve the use of around 5–7 injection and producing wells, are important, not just as a way of proving the viability of the technology on a small scale, but also as a means of building in-country technical knowledge, understanding, and capability, as well as a broader understanding of the value and

Figure 8: Roadmap for the Development of Carbon Capture, Utilization, and Storage in Southeast Asian Countries



CO₂ = carbon dioxide.

Source: Asian Development Bank. 2013. *Prospects for Carbon Capture and Storage in Southeast Asia*. Manila. <https://www.adb.org/sites/default/files/publication/31122/carbon-capture-storage-southeast-asia.pdf>.

future role of CO₂-EOR+. The primary goal of these projects would be to demonstrate several aspects of the technology, including:

- (i) CO₂ sourcing from a nearby anthropogenic source;
- (ii) transportation of the CO₂ from the source to injection wells at the selected oilfields;
- (iii) injection of CO₂ in a way that minimizes health and environmental risks;
- (iv) tracking reservoir response to CO₂ injection in terms of incremental oil recovery and associated CO₂ storage; and
- (v) monitoring the performance of the reservoir during and after CO₂ injection, including changes in geochemistry and geomechanical properties, the integrity of the wellbore, and any induced seismicity.

The pilot projects would also be expected to provide a wealth of data, the analysis of which could be used to establish protocols for data acquisition and interpretation during full-scale commercial deployment at a later stage. The pilot studies are expected to take around 5 years to be completed.

The Government of Indonesia and Pertamina currently favor the Sukowati project and are looking to secure financing. ADB envisages that this and possible other pilot projects, if successful, will pave the way for demonstration projects, possibly at the same field and/or others, involving the injection of much larger quantities of CO₂—of the order of 500–1,000 tons per day—into a number of wells over at least 10 years. It is hoped that these projects would confirm the technical and economic feasibility of CO₂-EOR+ in each case, leading to the financing and large-scale rollout of the technology on a commercial basis, involving the injection of at least 2,500 tons per day over 20 years or more and the storage of a significant share of Indonesia's total CO₂ emissions.

A number of issues still need to be resolved for the Sukowati project to proceed. At the field scale, there is a need for further assessment of how the faults within the reservoir will affect well communication, production rates, and carbon storage. Updates to simulation studies are also needed to predict reservoir performance, as well as a plan to monitor flow rates and the exact amount of CO₂ being stored. Additional work is also required to evaluate CO₂ purification and injection costs, as well as subsurface behavior of the injected CO₂, wellbore integrity, and communication between the pilot wells. The current timeline envisages that the pilot would start in 2023 and, if successful, the full field-scale project in 2027.

More broadly, more work should be conducted to improve the rule-of-thumb estimates of additional oil that could be recovered from other fields with CO₂-EOR using simplified reservoir models (Kuuskraa, Leewen, and Wallace, 2011), as well as more detailed assessments of the technical and economic feasibility of other projects. This would provide detailed information about the history of oil recovery and the potential CO₂ storage capacity for each field of interest. These assessments would need to include a pipeline routing study to identify the best sources of CO₂ for each candidate field.

The development of pilot and demonstration projects may need to explore potential funding from the multinational institutions and the possibility of obtaining carbon emission reduction credits. The funding for these projects and possibly full-scale commercial projects is likely to come from international financing institutions such as ADB.

B. Addressing Regulatory Barriers

Since CO₂-EOR+ is a new activity in Indonesia, it requires the implementation of a comprehensive legal and regulatory framework covering all activities related specifically to its use. It will need to be in place by the time a commercial-scale CCS project is ready for deployment (ADB, 2013). Work on developing a general framework has been undertaken in parallel with the identification of pilot and demonstration projects with assistance from ADB.²³ This has resulted in the preparation of a draft presidential decree, which was completed in March 2019—the first regulation specifically covering CCS of any developing country.²⁴ The framework, which builds on existing regulations governing the upstream sector and industrial activities, incorporates permitting requirements and, in its current form, covers all aspects of CO₂-EOR+ projects, including CO₂ capture from different types of sources; transportation via road, pipelines, and rail; the reception of the CO₂ at the oilfield; its injection into the field; and measurement, reporting, and verification (MRV) of CO₂ storage. The decree is intended to cover pilot and full commercial CCS projects and to be sufficiently detailed to give confidence to potential investors looking to pursue CO₂-EOR+ projects. The development of a more comprehensive regulatory framework at a later stage is expected to benefit from the lessons learned from the pilot projects.

The primary objective of the decree is to establish a performance-based system of permitting for the storage of CO₂. It sets out the standards by which CCS projects shall be permitted with the objective of mitigating the risks associated with such projects. A thorough understanding of legal and regulatory requirements to obtain permits is critical to the success of upstream projects of all types (Government of the United States, Department of Energy, 2017). The decree also provides mechanisms for coordinating the permitting process and CCS policy making more generally among government regulators, including the establishment of an interagency coordinating committee to ensure that regulatory actions are coordinated and information is shared among agencies. The decree also provides for the creation of a mechanism for public engagement at an early stage of project development to ensure a role for the public in decision-making so that local concerns are taken into consideration; to make efficient use of natural, monetary, and human resources; to promote community

²³ The draft decree was drawn up by a committee hosted by MEMRI in partnership with the Ministry of Environment and Forestry over July to December 2018. The directorate general of Oil and Gas, the directorate of Climate Change Mitigation in the Ministry of Environment and Forestry, the Special Work Unit for Upstream Oil and Gas Activities of SKK MIGA, the National Standardization Agency of Indonesia, LEMIGAS, Pertamina, and other government agencies also participated in committee meetings and reviewing drafts.

²⁴ CCS regulations have been adopted in Australia, Canada, and the US, while a framework regulation has been introduced in the European Union. Regulations are under consideration in the PRC and Mexico.

development and employment opportunities; and to safeguard health, safety, the environment, and other resources.

Under the proposed framework, a CCS permit would last the entire life of the injection project, covering all injection wells. The decree sets out the application process including requirements for providing detailed information to the lead regulator to be shared with the interagency committee. The specific technology to be used would be left to the discretion of the permit applicant, though regulators may grant a permit on specific conditions to ensure that the project operates in a manner compliant with health, safety, and environmental regulations. The information requirements for permit applications, which were based on permitting regimes in Australia, the European Union, and the US, are mandatory unless the applicant can justify why the information should not be required. Information requirements fall into the following categories:

- (i) technical and financial qualifications of the applicant,
- (ii) geological assessment data and modeling,
- (iii) project design and construction information,
- (iv) monitoring and emergency remediation response plans,
- (v) a mechanical well-integrity testing plan,
- (vi) an operating plan,
- (vii) a post-injection monitoring plan,
- (viii) a closure plan, and
- (ix) a seismic monitoring and risk mitigation plan.

The draft decree requires that all injection wells and other infrastructure are built using materials compatible with the injection of CO₂ to ensure the integrity of injection wells, pipelines, and equipment that can be damaged due to corrosion when CO₂ mixes with water or water vapor. Mechanical integrity tests are required to be completed and approved before injection can start and each year thereafter. The responsible minister may, at any time, undertake or require a CCS operator to take corrective measures to rectify significant irregularities, close leakages to stop or prevent the release of CO₂, or protect human health or property. The applicant must also carry out comprehensive analysis of the potential impact of earthquakes on the storage complex and surface facilities using empirical data and modeling. Regulators can deny an application for a CCS project permit if they judge that the project poses a significant risk to health, safety, the environment, or other resources, such as mineral and water resources. In making its decision, the regulator shall consider the safety and integrity of the site in the short and long term, including an assessment of the risk of leakage of CO₂ under the proposed conditions of use and of the worst-case environmental and health impacts.

The default period for monitoring under CCS permits once injection has ceased is 3 years for injection volumes of between 150,000 and 1,000,000 tons, and 10 years for over 1,000,000 tons. These periods are default periods only and can be shortened or lengthened by the regulator according to its assessment of the need for monitoring to ensure the safe operation of the injection site. Closure of the injection site occurs in three circumstances: (i) if the relevant conditions stated in the permit have been met; (ii) at the substantiated request of the operator, after authorization of the relevant minister; or (iii) if the minister so decides after the revocation of a

CCS project permit. In the first two cases, the operator is responsible for sealing the storage site and removing injection facilities, as well as monitoring, reporting, and implementing any necessary corrective measures as required by its permit. In the latter case, the minister shall arrange monitoring and corrective measures.

The draft decree provides for operators of CCS projects, including pilots, to report various types of data to government regulators throughout the duration of the project, from the initial application to well closure at the time injection ceases and during the post-injection monitoring period. The results of the pilot projects should be used to assess the need to modify the regulations governing permitting future commercial projects (ADB, 2013).

The decree exempts pilot projects involving small-scale injections of CO₂ of 150,000 tons or less from certain requirements. Other jurisdictions that have specific CCS regulations, including Australia, the European Union, and the US, have similarly exempted pilot CCS projects from full regulatory requirements to encourage investors. In particular, there is no requirement for post-injection monitoring of the CO₂ plume once injection has ceased as the small volumes involved would normally present little risk to health, safety, or the environment. Other types of post-injection monitoring such as the impact of seismic activity may still be required at the discretion of the regulator. A pilot project permit may also be exempted on a case-by-case basis from complying with long-term liability provisions requiring insurance or establishing a fund for any future costs associated with maintaining an injection well after injection has ceased.

There may be a need to draw up more detailed regulations concerning specific aspects of CO₂-EOR at a later stage to build on practical experience in Indonesia. These regulations need to be defined clearly as they have a significant impact on the evaluation of technical and economic risk by project developers (ITB and LEMIGAS, 2017). In preparation for large-scale deployment of the technology, it will be important for oilfield operators to start evaluating and mitigating this risk at an early stage. For example, a systematic well integrity assessment—an assessment of the risk of gas and fluids escaping in an uncontrolled manner from the wellbore—could be performed at fields where EOR is most likely to be feasible. In many cases, such risks can be minimized through minor remediation work during routine workovers. Regulatory requirements for well plugging during the abandonment phase can be reviewed and updated, if necessary. Other technical and safety risks associated with CO₂-EOR projects include the migration of the injected CO₂ into unintended areas and a lower rate of CO₂ retention than expected. The absence of detailed regulations concerning these risks will make risk assessments carried out by project developers less comprehensive and more complicated.²⁵ The results of risk assessments will, in turn, be of value in drawing up and refining regulations as the deployment of CO₂-EOR+ progresses.

²⁵ Risk assessments that currently exist for major CO₂-EOR+ projects in other parts of the world can provide the basis for designing appropriate assessments in Indonesia. Pilot projects will be instrumental in providing information about region-specific risks that might have to be included in future assessments.

C. Financial Incentives

There is also a need to review and recommend specific policies and tax incentives for CO₂-EOR+ in Indonesia. For large-scale commercial projects to take off in the country in the medium to long term, a significant financial incentive will undoubtedly be necessary, especially if oil prices fall. If there is no economic case for CO₂-EOR, then there will certainly be even less of a case for CO₂-EOR+ unless incentives effectively lower the price of the CO₂ delivered to an oilfield for injection. Demonstrating the technical feasibility of CO₂-EOR+ will count for little unless the technology proves to be financially attractive to upstream operators. In principle, incentives are justified by the emissions savings that investment in CO₂-EOR+ could achieve. The size of those incentives should take account of the marginal cost of emissions reductions in the rest of the Indonesian economy.

Incentives could take the form of a carbon tax credit, such as the 45Q tax credit mechanism recently adopted in the US (Box 5), or an emissions trading scheme, such as that being introduced in the PRC. Both approaches seek to place a price on carbon emissions, encouraging their use in industrial processes and their eventual storage. Implementation of such policies at an early date would provide clarity for potential investors. The framework should also take account of the “new market mechanism”²⁶ under the Paris Agreement, which is due to come into force from 2020, and any other bi- or multilateral mechanisms that provide credits for CO₂ stored in the ground.

Box 5: The United States 45Q Tax Credit Mechanism for Carbon Capture, Utilization, and Storage

This tax credit, named after the relevant section of the United States (US) tax code, aims to incentivize investment in carbon capture, utilization, and storage (CCUS) by providing credits to the entity capturing carbon dioxide (CO₂) once the gas is proven to be permanently stored. When the CO₂ is captured, the facility can choose to store it in deep saline reservoirs or sell it for commercial purposes, including enhanced oil recovery (EOR). Credits vary depending on the use of the CO₂. Following an amendment to the credit in 2018, the current value for deep saline storage was raised to \$50 per ton of CO₂, while that for commercial sale and/or use and EOR was increased to \$35 per ton. The credits are slated to last for 12 years for projects started within a specified time period; to be eligible for the credit, a new CO₂-EOR+ project would need to begin construction by 1 January 2024. The value of these credits will be adjusted over time to take account of inflation.

Source: Authors.

²⁶ The “new market mechanism” is intended to supersede project-based emissions reduction market mechanisms, such as the Clean Development Mechanism, by counting sector- or industry-wide emissions reductions.

CO₂-EOR+ projects demonstrating storage of anthropogenic CO₂ may also be eligible for carbon credits in the form of offset credits for emission reductions. While the same monitoring and modeling technologies apply to CO₂-EOR and other types of geological storage, operators of the former will need to make additional investment in MRV to characterize, manage, and ensure the long-term integrity of storage, as well as optimal EOR operations (as described in Section II). MRV requirements for both the operation and shutting-in of CO₂-EOR+ projects at the end of the field's life will be crucial for such projects to qualify for carbon credits. Monitoring protocols have been developed by groups such as the American Carbon Registry (American Carbon Registry, 2015) and are also under development through the International Standards Organization. These standards could be adopted by Indonesia with modifications to take account of local factors.

D. Developing In-Country Capability

The development of human capital will be an important element in achieving the successful demonstration and subsequent large-scale deployment of CO₂-EOR+ technology in Indonesia. In particular, learning and knowledge must be transferred from CO₂-EOR+ projects in other parts of the world. Capacity building among local stakeholders must occur across all aspects of project development: technical, financial, environmental, community engagement, regulatory, legal, and institutional (ADB, 2013). To this end, the partnership between ITB and LEMIGAS through the CoE for CCS and/or CCUS, the existing collaboration between LEMIGAS and Pertamina, and the help of experts assisting ADB are good examples of ways of building in-house capability. These should be continued and enhanced. The pilot projects would also facilitate building the expertise in planning, construction, operation, and completion of CO₂-EOR+ projects. The presence and involvement of local personnel throughout the project development cycle would also facilitate capacity building and minimize the need for international technical assistance by the time demonstration projects are deployed (ADB, 2013).

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Carbon Dioxide-Enhanced Oil Recovery in Indonesia

An Assessment of its Role in a Carbon Capture and Storage Pathway

This publication assesses the potential of carbon dioxide-enhanced oil recovery (CO₂-EOR) technology to mitigate climate change in Indonesia. Although the technology was designed to rejuvenate oil production in mature oilfields, its value in permanently storing CO₂ has recently attracted global interest. The publication concludes that CO₂-EOR could provide a win-win for Indonesia by improving oil production while also helping to reduce the country's rapidly rising greenhouse gas emissions. It proposes a pilot project as a critical first step to deploy the technology and provides insights on how to create a supportive regulatory environment and financial incentives.

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